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AGARDograph No.306

Occupant Crash Protection in Military Air Transport

(Protection contre l'Ecrasement des Occupants des Aéronefs de Transport Militaires)

NORTH ATLANTIC TREATY ORGANIZATION

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARDograph No.306

Occupant Crash Protection in Military Air Transport

(Protection contre l'Ecrasement des Occupants des Aéronefs de Transport Militaires)

by

Richard F. Chandler

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This AGARDograph was prepared at the request of the Aerospace Medical Panel of AGARD.

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Preface

In 1976, Dr R.G.Snyder, then at the University of Michigan, Ann Arbor, USA, completed his comprehensive report "Advanced Techniques in Crash Impact Protection and Emergency Egress for Air Transport Aircraft (AGARDograph No.221). Since that publication there have been several major developments in the field of crashworthiness and survivability. These relate to emergency crash landings and fire protection, understanding crash injuries, emergency evacuation, new seat development and other impact protection, new regulatory standards and other aspects of the problem in both fixed and rotary wing aircaft.

At the 40th Business Meeting of the Aerospace Medical Panel (AMP) 6 October 1983, London, United Kingdom, the Panel accepted a proposal from the Biodynamics Sub-Committee to sponsor a new AGARDograph that would review crash protection in aircraft in light of these newer developments. A detailed outline of the proposed topic was presented to the National Delegates Board (NDB) of AGARD in 1985, but the subject was considered too broad, as it included air vehicles not normally associated with military air transport. A revised proposal that was specifically tailored to occupant crash protection in military air transport was accepted by the NDB at its 62nd meeting in Paris, France, 26–27 March 1987. A contract was negotiated with Dr Richard Chandler, Norman, Oklahoma, USA early in 1989 to write this AGARDograph.

Préface

En 1976, le Dr R.G.Snyder, dépendant alors de l'Université du Michigan, Ann Arbor, USA, présenta un rapport très complet sur "Les Techniques Avancées de Protection contre les Impacts à l'Ecrasement et l'Evacuation d'Urgence dans les Aéronefs de Transport Aérien" (AGARDographie No.221). Depuis lors, des progrés notables ont été réalisés dans le domaine de la résistance à l'écrasement et la survivabilité. Il s'agit en particulier de l'atterrissage d'urgence et la lutte contre l'incendie, les blessures, l'évacuation d'urgence, l'étude d'un nouveau siège pour le pilote et d'autres mesures de protection contre les impacts, les nouvelles normes réglementaires et d'autres aspects du problème pour les aéronefs à voilure fixe et à voilure tournante.

Lors de la 40ème réunion du Panel AGARD de Médecine Aérospatiale (AMP) le 6 october 1983 à Londres, le Panel a accepté une proposition formulée par le sous-comité pour la biodynamique selon laquelle le Panel cautionnait une AGARDographie sur la protection contre l'écrasement qui devait tenir compte des derniers travaux effectués dans ce domaine. La proposition a été présentée en détail au Conseil des Délégués Nationaux de l'AGARD (NDB) en 1985, mais le sujet a été jugé trop vaste puisqu'il comprenait des véhicules aériens ne rentrant pas dans le cadre normal du transport aérien militaire. Une proposition modifiée, spécifique à la protection contre l'écrasement pour les occupants des aéronefs de transport militaires a été approuvée par le NDB lors de la réunion du 26–27 mars 1987 à Paris. Ainsi un contrat pour la rédaction de la présente AGARDographie a été signé avec Dr Richard Chandler de Norman, dans l'Oklahoma, aux Etats-Unis au début de l'année 1989.

Jack PLANDOLT, Ph.D.
Chairman, Biodynamics Committee
Aerospace Medical Panel

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Occupant Crash Protection in Military Air Transport

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SUMMARY

For many years, accident investigators have pointed out the need for improved seat and restraint systems for the occupants of aircraft involved in a crash. Carefully directed studies, beginning in the 1940's, provided the basis for improving the systems. Design guidance and seat specifications were developed from these studies. By 1970, it was possible to develop procurement specifications for rotary wing aircraft which were designed, from the beginning, to provide crash protection to their occupants. In the 1980's, this technology began to be applied to civil aircraft of all types. Regulations were developed in the United States for improved seats and passenger protection in small airplanes, transport airplanes, and helicopters. This report traces the progress of these developments, and summarizes the studies and decisions which led to the current state of the art. An extensive bibliography provides the sources of reports necessary for a reader who wishes to make an in depth study of the technology.

INTRODUCTION

In 1976, AGARDograph No. 221, Advanced Techniques in Crash Impact Protection and Emergency Egress from Air Transport Aircraft, by R. G. Snyder, provided a state-of-the-art summary of occupant protection technology for both aircraft and automobiles. Since that time, significant developments pertaining to occupant crash protection in aircraft have taken place. The present report provides the historical and technical background for those developments. The first chapter of this report presents the historical background for the problem of aircraft crash injuries, introduces the circumstances which led to the first research in this area, and provides a quick summary of the beginning research efforts. The second chapter considers the progress made from the early 1940's until about 1970. Basic studies in aircraft crash environments, injury and human tolerance, and seat and restraint system designs specifically for limiting injury were conducted during this period. This chapter closes with the development of the first military standards for aircraft crashworthiness. The third chapter considers the application of that technology to military aircraft, and closes with the efforts which led to the first defined requirements for crash injury protection in civil aircraft. After each chapter, a series of notes is provided which contain additional information or opinions of the author regarding the factual information being presented. References have been incorporated into an expanded bibliography pertaining to crash injury protection technology for aircraft occupants. This bibliography is given in Appendix A. A listing of data pertaining to crashes of transport airplanes during 1975 through 1986 in Appendix B, is provided to supplement the data given by Snyder (o.c.). Note that accidents and incidents which did not result in a crash are not included in this list.

The present report is intended to focus only on the history of significant developments in seating and restraint systems for improved occupant protection in aircraft crashes. As such, it should provide the reader a starting point for obtaining additional information by reviewing the references or other reports listed in the Bibliography. Limitations in time and space have precluded a discussion of closely related disciplines such as human tolerance to impact and injury criteria and the considerable progress made in occupant protection in automobile crashes which might also be applied to aircraft. There is, of course, extensive literature on these topics. This report has not attempted to review the development of technology pertinent to other important aspects of aircraft crashworthiness, such as crashworthy fuel systems, structural design, ditching and emergency escape. An introduction to all these topics is given in the U.S. Army Crash Survival Design Guide (U.S. Army Aviation Research and Technical Activity Technical Report 89-D-22 A-E), which is in its fifth edition as this report is written. That five volume guide lays the groundwork for design of crashworthy aircraft. It should be the first report to be reviewed by any person seriously interested in such design.

Since this report is primarily a summary of work done by others, the units of measurement used by the original author of the work have been retained throughout. Every effort has been made to detect and correct errors in this report. However, it seems that in a work of this magnitude, some errors are inescapable. The author regrets any inconvenience they may cause, and would appreciate learning of any errors or important omissions.

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* Mr. Chandler is the former Manager of the Protection and Survival Research Laboratory of the Federal Aviation Administration Civil Aeromedical Institute.

Chapter 1: HISTORICAL BACKGROUND

The death of Lieutenant Thomas Selfridge, a 26 year old West Point graduate who had volunteered to be a passenger on a demonstration flight piloted by Orville Wright at Fort Meyer, Virginia on September 17, 1908, forecast the need for protection against crash injury.[Note 1] In the next three years, there were thirty-three crashes in which the pilot was killed, and two crashes in which a passenger was also killed (Villard, 1968). However, in those pioneering times, the problems of aircraft structural reliability and the limitations in ability to control the aircraft overshadowed the problem of injury protection. Reports of accidents occasionally included references to lack of pilot restraint.
For example:

> "The pilot, who was inexperienced, was making a steep gliding descent, when apparently he slipped out of his seat, having no belt, and fell forward on to the control column, thus causing the machine to bunt on to its back. The pilot fell out and was killed." (Brett, 1933),

or

> "The pilot was not strapped into his seat, and he fell out whilst making a steep gliding turn." (Brett, o.c.)

With reports such as these, safety belts intended to keep the pilot in his seat during flight maneuvers soon became common.[Note 2] The monoplane "Antoinette" had a belt which was rigidly attached to the fuselage, so that it "tended either to break as a result of impact or else hold fast and inflict internal injuries to the occupant" (Villard, 1968). These belts were sometimes attached to the airframe by elastic shock cords in an attempt to increase comfort or reduce injuries. An early report of the performance of such a safety belt in a crash was given by Robert Esnault-Pelterie. On June 18, 1908, he set out on a short trial flight in the R.E.P. monoplane, and failed to retard or cut the motor when descending. The machine hit the ground at full speed, and despite an "elastic" safety belt he was thrown against the fuel tank with such force that he broke one of its steel supports. The after-effects of his injuries caused him to give up piloting of aircraft, although he occasionally rode as a passenger (Villard, o.c.). When the first military pilot in the United States decided to install a safety belt in U.S. Army Aeroplane No. 1 in 1910, he resorted to using a modified leather trunk strap (Foulis, 1960).

Fryer summarized early work which led to the development of safety harnesses (Fryer, 1962). Protective clothing for providing resistance to penetration of the pilot's body by broken wooden airplane structure during a crash had been suggested by Latham. However, there was little interest in developing a means for restraining the pilot in the aircraft during a crash, perhaps because of the danger of being crushed by the engine (placed just behind the pilot in many early airplanes) or the concern of being trapped in the cockpit if the airplane turned over. Pryce, observing that some aviators had been saved from serious injury by becoming entangled in wires which prevented their impact with the ground during a crash, suggested that a safety belt would save lives. A 1912 advertisement by A.V. Roe for a safety belt apparently incorporating elastic cords "As supplied to the Army Aircraft Factory" is known, but the results of using the restraint are unknown. It was also reported that Twombly sold fifty samples of a form of shoulder harness for airplane pilots to the United States Government for tests in 1912, but again, the results of the tests are unknown.

In a report written in 1913 but not published until 1915, H.V. Wells recounted his observations while at Eastchurch Flying School (Wells, 1915). In airplanes with the engine in front and the pilot well behind, he found that the engine would take the shock of a crash, and the portion of the airplane directly behind the engine would crush while the pilot's seat and structure behind would suffer little damage. Nevertheless, serious injury could occur when the pilot's body came to a sudden stop "due to a safety belt or an outstretched hand," so that the head bent forward and struck some portion of the aircraft or forcibly wrenched the neck. He suggested two solutions: a safety belt having shoulder straps; or providing some yielding material in front of the pilot where the head would strike. He also discussed the use of safety belts and observed that most pilots were in favor of their use, but were concerned that belts would hold the pilot in the seat if the airplane turned over in a crash so the pilot would be crushed, and that belts could not be released rapidly and could trap the pilot in a crashed airplane that was burning. He concluded that safety belts were necessary for in-flight control of the airplane, but they should be provided with some easy and reliable release mechanism so that they could be undone just before a landing. While these recommendations were consistent with the attitude that safety belts were then intended only for in-flight safety, Wells apparently soon changed his opinion. In 1916 he strongly urged that the belt be attached to the airframe and not just the seat, so that the belt could restrain the pilot during a crash (Wells, 1916).

John Domenjoz, chief pilot and factory instructor for Bleriot, conducted exhibition flights in Europe, South America and the United States in the years 1914 - 1916. During the course of his exhibitions he flew inverted for up to a minute and twenty seconds, a feat that earned him the sobriquet of "upside-down Domenjoz" (Crouch, 1982). His Bleriot Type Onze aircraft, built in July 1914, was equipped with a leather restraint harness consisting of a wide belt around the torso, to which were attached dual shoulder straps and straps running under the bucket seat to hold the pilot in the seat during inverted flight. The belt was also attached to the lower longerons of the airframe by two belts in back. His exhibitions followed the flights of Adolphe Pegoud, who in 1913, in a structurally modified 1911 Type XI Bleriot equipped with a "special harness", performed outside half-loops and full inside loops.[Note 3]

Cruciform type torso restraint systems did not incorporate a safety belt or other lower torso restraint, so the pilot could easily slip forward under the harness during a crash, an action which would tend to increase chest, upper abdomen, and upper vertebral column injuries. One such restraint, used in the Albatros D.V fighter during the first World War, is shown in Figure 1 (taken from the illustrated parts manual for the Albatros D.V). The shoulder straps in this restraint were fastened to a fuselage former behind the bucket seat, and the lower straps were attached to the seat support frame, ahead of the seat. The free ends of the straps were equipped with fittings so that they could be fastened together around the pilot. The exact position of the fitting depended on the adjustments of the straps, but there is no possibility that the lower straps could be positioned to provide effective and safe lower torso restraint.[Note 5]

It was during the first World War, when the belligerents began to recognize that the airplane was a factor in battle, that the critical nature of replacing trained pilots whose lives were lost while flying forced a careful look at the reasons for these losses. One study concluded that only 2 percent of the flyers were lost as a result of action by the enemy, 8 percent were lost due to a fault of the engine or plane, and the remaining 90 percent were lost because of "failure of the flyer himself" (Air Service Medical, 1919). These findings led to the emphasis on accident prevention efforts to reduce the 90 percent loss, with strong programs in airman selection, training, medical monitoring, and continual education, and to the development of the concept of airworthiness to reduce losses due to engine or airframe failures, but did little to promote the development of techniques for crash injury protection.

Nevertheless, some examples of progress towards crash injury prevention can also be found. For example, medical officers observed that in one aircraft, more than half the injuries sustained in crashes were caused by the aviator striking his head against the cowl. After following a suggestion that the cowl be cut so as to allow 8 inches or more clearance in front of the pilot, head injuries "were practically eliminated" (ibid.). Likewise, a suggestion to use a simple shock absorber between the aircraft and the restraint system "decidedly reduced" the number and extent of injuries to the upper abdomen and ribs (ibid.). The use of safety belts as a means of protection from injury in crashes was officially recognized. In 1918, the "General Rules and Regulations Governing Flying on Individual Fields," (Wilmer,1920) contained the following instructions regarding safety belts:

> "17. All machines must be equipped with safety belts for pilot and passenger.
>
> 18. Always use safety belts. In case of accident, do not release the belt until after the accident. It will probably save injury, especially if the machine turns over."

One aircraft crash injury which occurred in 1917 turned out to be of particular importance to the future of aircraft crash injury research. Hugh De Haven, then a young cadet in the Canadian Royal Flying Corps, was rammed from behind at 500 ft. altitude during gunnery practice, damaging the right wing and tail of his Curtiss Model JN4 airplane (De Haven, 1969). As a result of the subsequent crash, De Haven suffered two broken legs, minor lacerations and bruises, and ruptured liver, pancreas and gallbladder. The other three occupants in the two planes suffered fatal head injuries. When he returned to duty after a six month recovery period, he was assigned to Squadron Headquarters at Armor Heights, near Toronto, Canada, where pilot training was conducted. The frequent crashes at this facility, sometimes as many as two in one day, provided De Haven the opportunity to relate the causes of injury to the accident pathology. He concluded that his own injury was caused by the "safety belt" provided in his airplane, described as *5-6 inches wide with a narrow pointed 6 inch buckle in the middle*. He also noted that wooden longerons in the cockpit area could break and impale pilots in moderate crashes, and that solid structure and objects in front of the pilots head were often the causes of fatal head injuries. When De Haven attempted to explain the causes of extreme injuries in obviously survivable crashes, and suggested that these injuries could be reduced by better engineering and design, he encountered the attitude that injuries in a crash were a matter of fate, that flying was dangerous, and the best way of preventing injury was to stay on the ground. The end of the War also ended De Haven's concern for crash injuries, at least for a time.

The end of the war in 1918 also appeared to signal the end of military concern over crash-related injuries. The restraint systems in use were continued, with little thought to further improvement. One version of the cruciform type torso restraint was the British Sutton harness. The Sutton harness was "made of four stout webbing straps securely fastened to the aircraft, one over each thigh and one over each shoulder. These straps had brass eyelets about one and one-half inches apart which made the harness readily adjustable to any size of pilot as he strapped himself in. First, eyelets of the thigh straps at a suitable length were threaded over a cone-shaped pin and then the shoulder straps were similarly threaded on the cone which was positioned in the region of the abdomen. A hole of about three-eighths of an inch in diameter was drilled through the cone-pin near the top. When all four straps were in position, a robust polished-steel split pin was passed through the hole to secure the straps in position. A stout rawhide thong was attached to the head of the split-pin. When the thong was pulled and the split-pin withdrawn, the harness fell apart due to the cone shape of the pin on which the eyelets were threaded." (Moore, 1963). Fryer (1962) discussed the reports of Watson-Jones (1941) and Cade (1941) which described crash injuries resulting from the use of the Sutton harness or the safety belt restraint systems. Such injuries included fractures of the upper thoracic vertebrae, head lacerations, concussion, and strangulation by the harness, and a high incidence of fatal head injuries in pilots when only the safety belt was used. The work of Pekarek (1941) and Gilson et al. (1943) resulted in modification of the Sutton harn ss concept by lowering the common point of the restraint straps so that the lower straps provided some measure of lower torso restraint.

In the United States, suggestions that aircraft be designed and constructed "so that they crash well" (Doolittle, 1929) went largely unheeded, although early civil regulations did specify requirements for seat belt strength with the intention that they be useful in a crash, and that the force be applied at a 45 degree angle relative to the longitudinal axis of the aircraft (Air Commerce Regulations, 1929; 1934). Results of military aircraft accident investigations continued to show injuries to the face and head when the safety belt was used in a crash. In 1936, Lt. Col. M. C. Grow, Chief Flight Surgeon of the Army Air Forces, investigated the crash of a plane in which both occupants died from basal skull fractures, but had no other serious injury. When he inspected the aircraft, he found that the structure containing the front and rear cockpits was intact but that the center of each instrument panel was damaged and bloody from head impact. As a result of this crash, and the many others which he had observed, Grow began development of a modified restraint with shoulder belts. Comparative tests of the restraint system suggested by Grow and the lap belt were conducted by Armstrong (1937, 1939) on a swing seat test device using human volunteers, but were terminated at 15 g, the limit of the recording instruments available. He found that a sudden deceleration of 8 g's or more would cause the body to violently jack-knife over the lap belt, but decelerations up to 15 g were tolerated without any displacement of the body and without significant discomfort. He estimated that one could live through a deceleration of somewhere between 30 and 50 g with the shoulder type safety belt if the belt and seat did not fail.Note 5 Armstrong also suggested the possibility of inflated rubber seat backs in transport aircraft, so that the back of the seat would act as an upper body support for the passenger seated behind the seat.

The restraint system suggested by Grow was eventually developed and installed in some United States airplanes during the World War II. In this development, the lower ends of the shoulder belts fitted over the tongue of the safety belt buckle so the shoulder belt and safety belt could be simultaneously and easily released. The aft ends of the shoulder belts were attached to aircraft structure through a spring tensioned locking mechanism so that the pilot could lean forward while in the harness, but could also lock the harness in a rearward position in time of emergency (Figure 2).

Hass (1943, 1944) studied injuries in crashes of training airplanes in which the pilots were restrained by lap belts. He found the typical injury patterns, and made several suggestions, including shoulder harnesses, overhead crash bars, elimination of sharp edges and projecting controls, switches, throttles and similar structures in the pilot compartment, seats which bend rather than shatter when large forces are applied, and that seats should be supported on shock absorbers designed to permit the seat to move in the vertical direction in response to crash forces. His strongest suggestion was that a method should be devised to eject the occupants from the fuselage while still strapped in their seats, with parachutes automatically opening, a technology that had already been developed and was being operationally applied in Europe.Note 6

In Germany, the development of high-speed aircraft led to a new operational problem. The traditional method of leaving a disabled aircraft by bailing out with a parachute became impractical. Not only did the increased air pressure make it difficult to climb over the side, but it became increasingly difficult to clear the empennage or the propeller (of a pusher type airplane). The development of a catapult seat to throw the pilot clear of the aircraft began in 1938 (Ruff, 1981). Analytical studies and trial ejections, had been conducted at the Heinkel aircraft facility by 1940 (Richter, 1940a 1940b).

Questions raised regarding the tolerance of the pilot to the loads imposed by the ejection seat led to what was possibly the first research study that could be termed "biomechanics of impact." Arno Geertz, of the Heinkel Aircraft Company, studied under the direction of Dr. G. Madelung and Dr. S. Ruff at the Technische Hochschule in Stuttgart. His doctoral thesis, submitted in November 1944, described his work investigating human tolerance to ejection stress (Geertz, 1944). This thesis presented an analytical discussion of the dynamics of ejection from aircraft, the development of methodology to measure acceleration in laboratory simulations of ejections, and research on the biomechanics and impact tolerance of the spinal column. It contained a tolerance curve with distinct limitations based on circulatory disturbance, static strength of bones, and dynamic strength of bones, for impact durations greater than 0.5 seconds, between 0.5 and 0.005 seconds, and less than 0.005 seconds, respectively.Note 7 Geertz also reported the influence of seat cushion construction on "reinforcement or damping" of acceleration, with some types of cushions showing reinforcement in excess of 20 percent. The success of the ejection seat project led to a directive by the Air Ministry of Germany in the fall of 1944, instructing that all fighter aircraft, including prototypes, be provided with ejection seats (Lovelace, 1945).

Ruff also described human tests on a swing seat, similar to that used by Armstrong (Ruff, 1941). One goal of these tests was to study the effect of seat belt anchorage spacing. Tests up to 18 g at an impact duration of 0.1 second were tolerated without injury. His report included comments on 3 years of flight experience gained after the test results were implemented, indicating that the human tests were probably conducted in 1937 or earlier. Ruff concluded that crashes exceeding 20 g could be accommodated without injury with proper seat and restraint design. Among the design criteria recommended were a static load harness strength of at least 3,500 kg, with the load distributed over as large an area as possible (German belt plates had an area of about 550 square centimeters), and mandatory use of a shoulder harness with fastening points at least 40 to 50 centimeters above the upper edge of the seat. Ruff also suggested the use of a shoulder harness locking reel with three latch positions: a low tension position to allow comfort and movement during normal operation, a locked position for use in bumpy weather, and a high strap tension, locked position for preloading the harness straps in case of danger. For vertical (seat to head) acceleration he suggested that the forces should be limited to 1,500 kg if they act for more than 0.005 seconds. If no shoulder harness is used, as in passenger aircraft, he recommended that at least 80 to 90 centimeters of free space be provided ahead of the belt fastenings to reduce head impact.

Schneider described protective measures for spinal injuries encountered with aircraft having skid type landing gear (Schneider, 1950). While the analytical portion of this brief report is concerned mostly with energy management in crashing aircraft, Schneider also discussed the importance of seat pan angle in determining spinal column loads and the experience of thoracic vertebrae fractures complicated by the stiff support provided by a backpack parachute and a tight shoulder harness.

These reports represent only a small portion of the findings that resulted from over 200 volunteer ejection seat tests, 60 successful ejections in operational aircraft and numerous investigations of injuries sustained in crashed aircraft conducted in that program. Nevertheless, they serve to illustrate a significant beginning of biomechanical studies of seat and restraint systems in Germany in the early 1940s.

Similar studies were also conducted at the Royal Air Force Institute of Aviation Medicine in Great Britain and in Sweden. In Great Britain, initial tests were conducted in 1944 on a rocket-propelled sled and produced accelerations of about 12 g for the first 0.1 second, with a total impact duration of 0.175 seconds (Stewart, 1946). Since it was felt that the resulting 6 foot acceleration distance was not representative of the ejection seat applications, additional work was carried out on three ejection towers at the Martin-Baker Aircraft Company and a fourth at the Armament Research Department. Reputedly, hundreds of live tests were conducted on these devices. As a result, it was concluded that it was probably unwise to subject a person to accelerations along the spinal column which were greater than 5 g in the first 0.01 second or to final values greater than 25 g, and that an intimate relationship exists between accelerations in the seat and on the person. Recommendations relative to restraint systems included the use of combined parachute and safety harness with an inertia lock on shoulder attachments and tensioning gear for the lower attachments, and dynamic tests, either on the pendulum or the track, to be carried out for new harness designs.

In Sweden, experiments to find a safe way to abandon an aircraft at any speed and altitude began in 1939 (The Aeroplane, 1953). The Royal Swedish Air Force and Svenska Aeroplan AB (Saab) provided an ejection seat for the Saab J21 airplane. This twin-boom pusher-type fighter aircraft was first flown during World War II, but deliveries did not begin until 1946. Placing the propeller behind the pilot provided excellent visibility but made it difficult to bail out of the cockpit. The first successful dummy ejection with the Saab Model 1 ejection seat was accomplished in January 1942, with the first live ejection being successfully completed in July, 1946.

Captured German ejection seats formed the basis for early experiments in the United States. A 30-foot ejection tower constructed according to directions from Dr. E. J. Baldes of the Mayo Clinic served as the facility for early tests with ballast or human subjects in the seat. Vacuum tube acceleration transducers were used to obtain accurate acceleration measurements of the body. These were placed on human subjects on the top of the head, the acromium, and the crest of the ilium, as well as on the ejection seat. Arm rests were also instrumented to measure load. Tests with human subjects were completed in December 1945. These measurements and observations of high-speed motion pictures of the tests led to the realization that the dynamic response of the occupant must be considered in optimizing the thrust-time characteristics of the catapult. This task was assigned to the Frankfort Arsenal. Kroeger (1946) described the initial results of the work. His analysis modeled a system with two elastically coupled masses, one mass representing the body of the pilot and the other representing the seat, with the elastic link representing the parachute pack, life raft, hip muscles, and so on. An electrical analog of this system, was constructed to allow convenient prediction of body acceleration as a function of catapult thrust-time characteristics, and a full scale mechanical analog was constructed for testing of catapults. Although rudimentary, these analogs predicted the common use of computer analysis and the development of anthropomorphic dummies with realistic dynamic response.

The conclusion of the war in 1918 had temporarily ended Hugh De Haven's ability to work towards reducing crash injuries, but a minor automobile accident in 1935 caused him to realize that engineers still didn't know how many times people were hurt or killed by things that could be easily changed. In 1936 he urged the U.S. Bureau of Air Commerce to undertake a program in which doctors, engineers and safety groups could work together to reduce crash injuries in aircraft. After several meetings with James C. Edgerton, Chairman of the Special Committee for Aviation Medicine (a group established to define human capabilities and limitations for sub-stratosphere flight) he was able to present his ideas to the Committee. Unfortunately, the Committee came up with a discouraging view of such a project. Aside from the cost of building an acceleration deceleration facility and the problem of extending accident data from Federal investigations to civilian engineering groups with the threat of legal involvements, the Committee felt most particularly that doctors having charge of persons injured in civil aircraft accidents would not divulge the nature and extent of injuries because of ethical obligations (De Haven, 1959). He again attempted to interest other groups in a careful study of the causes of injury, but was repeatedly rejected. Engineers believed that improvements in aircraft for meaningful crash injury reduction would result in unacceptable weight and cost penalties. Pilots believed that any money spent for injury prevention could be more effectively spent for accident prevention. He was able to gain the interest and cooperation of a few accident investigators. From 1935 to 1941 De Haven personally investigated aircraft crashes in which there were both survivors and fatalities. He was unable to estimate the forces involved in the aircraft crashes and redirected his efforts to studies of falls, where the fall distance and impact velocity could be more accurately estimated. De Haven gained access to the wards of Bellevue Hospital in New York City, where he began a study of the impact environment which caused skull fractures. This work led to research of suicide attempts by jumping and falls from heights of 50 to 150 feet. His combined engineering and pathological study of the apparent miraculous survivors of these falls (De Haven, 1942) confirmed his theories regarding protection against crash injury. This study attracted the attention of Jerome Lederer, a former engineer in charge of loss prevention for Aero Insurance Underwriters who was then Director of the Safety Bureau of the United States Civil Aeronautics Board (CAB), and of Dr. Eugene F. Du Bois, head of the Department of Physiology at Cornell University Medical College and chairman of the Committee on Aviation Medicine of the National Research Council (NRC). Their support led to the establishment of a joint CAB NRC project for Crash Injury Research (CIR) at the Cornell Medical College in New York City in 1942. The studies conducted by the CIR project and its derivative organizations ultimately formed the basis for much of the progress in crash protection for occupants of aircraft and automobiles.

Notes for Chapter 1

Note 1: Selfridge was an active participant and secretary of the Aerial Experiment Association, a group formed by Dr. Alexander Graham Bell to "build a practical aeroplane which will carry a man and be driven through the air on its own power." Glen Curtiss joined this group in 1907 as director of experiments and chief executive officer. Selfridge is thought to be the principal designer of the Red Wing biplane, which made its first, and only, flight on March 12, 1908, over the frozen lakebed of Lake Keuka, New York. The aeroplane flew for over 318 feet, then rolled over on its side and crashed (it had no lateral stability). The Association continued its experiments, and finally achieved success with the White Wing biplane. On May 22, 1908, this aircraft flew a distance of 101 feet and landed successfully, with Glen Curtiss at the controls. The next aircraft was the famous June Bug, one of the first airplanes to be equipped with ailerons on the wing tips for improved control. This development led to a protracted courtroom battle between the Association and the Wright brothers, who maintained that the movable wing tips were an infringement of their patented wing warping principle.

Selfridge was thus a technically qualified observer when he flew with Orville Wright on September 17, 1908. During this flight, a crack developed in the starboard propeller of the Wright Type A Flyer, and caused violent vibrations. Orville Wright was apparently unable to control the aircraft, which went into a nosedive and crashed. Selfridge died of a compound comminuted fracture of the base of the skull.

It might be thought that his skull injury would have promoted the use of helmets for protection. After all, helmets, in one form or another, had been used since pre-historic times to protect the head from impact. A few pilots eventually adapted protective headgear used in sports for their flying, but the practice was not widespread. As late as 1926, medical advice recommended the use of helmets made of soft leather, with "no hard or unyielding substance about it", and that it should "fit snugly about the face, otherwise the use of ear plugs or powder puffs (to reduce the constant roar of a high powered motor) will be nullified by the ballooning of the helmet" (Bauer, 1926).

Note 2: There were no guidelines which these early pilots could use while selecting their safety belt installation. Since these belts were intended to keep the pilots from falling out of their airplane, it seems logical that early pilots would consider a design which had been developed to keep workers from falling from high buildings — the industrial safety belt. This may explain the placement of the safety belt around the waist of the pilot. Then, as now, many industrial safety belts simply fastened around the waist. We now know that placing a safety belt around the waist does not provide good crash protection. The internal injuries caused by these belts in early crashes are now well understood. But, before we become too concerned about the lack of insight possessed by our early aviators when selecting safety belts, let us remember that the "gunners safety belt" used in many modern combat aircraft is a direct descendant of these early installations. Unfortunately, the passage of time has not improved the injury protection offered by those belts.

Not all early pilots followed the example of the industrial safety belt when choosing their restraint. Photos of Lincoln Beachey, the well known stunt pilot, in his

Curtiss Model D biplane, show a belt installation with the belt firmly over the hips, at the "proper" 45 degree angle, so that restraint forces acted on his pelvis, rather than his abdomen. Beachey met his death in 1915 while flying a new monoplane specially built for his exhibition work. His last stunt was to dive vertically from 3500 feet altitude, with full engine power (a stunt he had accomplished before in the Curtiss Model D). He apparently misjudged the speed of his descent and pulled up too sharply. Both wings broke off the monoplane, and he crashed into the San Francisco Bay and was drowned. His body was pulled from the wreckage 35 minutes later. There is no record of the function of the seat belt in this crash, but it would be unfortunate if the belt had protected him through the crash, only to contribute to his death by drowning because it could not be quickly released. As an interesting aside, it is speculated that Beachey misjudged the speed of his descent because the new monoplane had a windscreen which protected him from the blast of wind in his face.

Note 3: The first man to fly a loop was apparently Lt. Petyr Nesterov of the Imperial Russian Air Service. He demonstrated the maneuver at Kiev in August 1913, one month before Pegoud's demonstration. Unfortunately, no information is known regarding the harness used by Nesterov.

Note 4: Cruciform type restraints were widely used by pilots on both sides during World War I. One factor which may have promoted the use of these shoulder restraints is seldom mentioned. Most aircraft in use at that time did not have "trim" control on the ailerons, so that the pilot was required to apply significant force to the control stick throughout the flight. If no shoulder harness was in use, the forces generated when the pilot pulled on the control stick would be reacted by the muscles in his lower back. This would be a tiring action. The restraint harness could relieve this back strain by transferring the forces from the shoulders directly to the airframe.

Note 5: We should, perhaps, evaluate these results with some caution. In another section of his 1937 report, Armstrong describes his acceleration recorder as a brass weight constrained by a coil spring which indicated acceleration by scribing the displacement of the weight on a rotating recording drum. Such a device would be under-damped by the low mechanical friction in the system. While sufficient for the sustained acceleration studies which were Armstrong's primary interest, it could introduce significant error when used for measuring the rapid-onset impacts of the swing seat.)

Note 6: This report is intended to show the progress in developing crash injury protection systems for occupants of transport aircraft which are usually equipped with fixed seats rather than ejection seats. The development of ejection seat technology will not be discussed except for those areas which have direct application to fixed seats.

Note 7: This tolerance curve was included in a later summary of the research by Ruff (1950), and was used by Eiband in his summary of literature pertaining to human tolerance to rapidly applied accelerations in 1959. Later it was adopted for the design of fixed seating systems for U.S. Army aircraft in the Crash Survival Design Guide (Turnbow, 1967), and as part of the requirement in the first military specification for crashworthy aircrew seats [MIL S 58095(AV), 27 August 1971].

CHAPTER 2: POST WAR PROGRESS

CRASH INJURY RESEARCH PROJECT (CIR)

At the inception of the Crash Injury Research Project in 1942, aircraft accident investigators were concerned almost exclusively with determining the cause of the accident. One of the first CIR tasks was to develop accident investigation forms which could be used to systematically record injuries. During the war years, investigators of the Civil Aeronautics Board were provided forms on which, in addition to all the accident details, causes of injury and injuries resulting from the causes were carefully reported. Through cooperation with various state police, U.S. Army and U.S. Navy safety groups, similar investigations were undertaken by some states and the military. By 1943, a pilot study consisting of data from thirty accidents had been recorded and analyzed (De Haven, 1943). By 1945 these data had been expanded into a data base describing 185 accidents of light aircraft involving 308 occupants. (De Haven, 1943, 1945). As a result of studying the accidents, De Haven concluded:

(a) In accidents where the cabin structure was distorted but remained substantially intact, the majority of serious and fatal injuries were caused by dangerous cabin installations.

(b) Crash force -- sufficient to cause partial collapse of the cabin structure -- was often survived without serious injury.

(c) The head was the first and often the only vital part of the body exposed to injury.

(d) Fundamental causes of head injury were set up by heavy instruments, solid instrument panels, seat backs, and unsafe design of control wheels.

(e) The probability of severe injuries of the head, extremities and chest were increased by failure of safety belt assemblies or anchorages. In one type of aircraft studied, safety belt failure occurred among 70% of the survivors.

(f) Failure of the 1000 pound safety belt occurred in 94 cases among 260 survivors of these crashes. Only 7 survivors showed evidence of injury of abdominal viscera; 2 of the injuries were classified as serious.

(g) The tolerance of crash forced by the human body had been grossly underestimated.

(h) If spin-stall dangers were lessened and safer cabin installations used, fatal or serious injuries should be rare in the types of aircraft studied except in extreme accidents.

The results of this study were provided to manufacturers, four of whom had indicated their intention to provide improved spin performance, cockpit structure, safety belts instrumentation panels, etc., in forthcoming models.

Funding for the Crash Injury Research project had been provided under a contract from the U.S. Office of Scientific Research and Development until 1946, when the Office was terminated following the end of the war. In order to continue his work, De Haven obtained support from the military services, the Civil Aeronautics Administration (CAA), the Aircraft Owners and Pilots Association (AOPA, representing the operators of small aircraft) and the Aircraft Industries Association (AIA, representing manufacturers). While this broad based support was a welcome indication of interest in crash injury protection, it was also an indication of the difficulties which would be encountered in obtaining regular funding in the postwar recovery period. The early studies had been done by De Haven with only a small staff ... an assistant, a secretary, and an analyst-librarian. With the resignation of his assistant in 1947, and with no funds to fill the vacant position, the CIR project was severely handicapped. This situation was rectified in 1949 when A. Howard Hasbrook joined the staff. Hasbrook, a pilot since 1934, had extensive experience as a flight instructor, test pilot and agricultural pilot, and like De Haven many years before, had recently been seriously injured in a plane crash. Hasbrook became director of Accident Investigation for the CIR in 1950.

De Haven and Hasbrook studied eighty-two accidents involving surplus, single engine military trainer aircraft flown by civilian pilots to determine the use and effectiveness of the shoulder harness in combination with the safety belt (De Haven and Hasbrook, 1951, reprinted 1956). In 68% of these aircraft, the shoulder harness had been removed, in 9% the harness was in place but not used by the pilot during the crash, and in only 23% was the harness used. In one-third of the accidents where the harness was used, the pilot had neglected to lock the take up reel which attached the harness to the airframe, so the harness was ineffective. Reasons for removing or not using the shoulder harness included inconvenience of use, discomfort, difficulty in reaching controls when the harness was used and locked, difficulty in adjusting the harness to fit, lack of understanding that the purpose of the shoulder harness was to reduce injury in a crash, and belief that the use of the shoulder harness often caused broken necks in a crash. Nevertheless, the study showed statistically significant reductions in injuries when the shoulder belt was effectively used, until such point where crushing injures were sustained due to collapse of the structure surrounding the pilot.

The conclusions of these early CIR studies reflect some of the problems which were encountered in promoting crash protection. A widely held belief was that "1000 lb" (proof load in tension) belt assemblies in common use were sufficient because the human body could not withstand higher forces. This belief (probably based on the reputation of safety belts which were located over the abdomen, even though most safety belts were then located over the pelvis) was one of the first obstacles to overcome. In 1947, the accident data base, which had grown to include 833 cases of injury, was reviewed to determine the frequency of abdominal injury due to the safety belt. Three hundred and fifty-four of these injuries were in severe but survivable crashes, but only 3 survivors and 5 fatalities showed any evidence of internal abdominal injury (De Haven, 1947). In 1951, De Haven reported that Mr. Roger Griswold had developed a new safety harness along the lines suggested by CIR. This harness was the type now commonly used in automobiles, where a single belt forms a diagonal torso restraint and then passed through the buckle to form the safety belt for the pelvis (De Haven, 1951). He was most enthusiastic about the fact that the shoulder belt must be worn if the safety belt was worn. Nevertheless, he cautioned that the ultimate effectiveness of harnesses could only be judged from accident reports. In 1953, De Haven reported on the first design applications of his suggestions (De Haven, May 1953). The Helioplane Courier "designed to be the safest small airplane yet produced" and the Meyers 145 both included the Griswold type restraint as standard equipment for all occupants.

While De Haven was attempting to obtain support for improvements in design and use of seat belts, a report of injuries sustained in the crash of a Viking transport airplane on October 31, 1950, was made public (Teare, 1951). While the intent of this report was to encourage the adoption of rear facing seats in transport airplanes, a statement that 16 of the 28 fatalities were killed by injuries resulting from "acute flexion of the body over the safety belt" received widespread dissemination in the American press under headlines like "The Dangerous Safety Belt" (Scientific American, December 1951). The implication that over half the fatalities were caused by safety belts resulted in an increased public resistance to the use of aircraft safety belts, and threatened to nullify the attempts made by De Haven and his sponsors for improved design and use of safety belts and shoulder harnesses for small aircraft as well as for transport airplanes. Dubois (1952) responded to the report, and concluded that the injuries were due to causes other than the safety belts, and that the typical signs of injury due to safety belt contact were absent from the victims. Of course, this response did not receive the attention of the original report, and CIR found it necessary to report opinions and analysis which emphasized the benefits which could result from proper forward facing seat and restraint systems (De Haven, 1952; Hasbrook, 1956). Those reports also contained a critical analysis of potential problems with rear facing seating systems in an apparent attempt to balance the criticism levied against forward facing systems. Those reports have since been frequently used by those who oppose rear facing seat installations, even though De Haven was one of the first proponents of rear facing seating, having suggested the concept in 1936 (Lederer, 1971). Proponents of rearward facing seats were quick to respond (e.g., Fryer, 1958), continuing a conflict which has not yet been conclusively resolved in favor of either seat position.

The continued concern over possible injuries from the safety belt resulted in a special grant from the CAA to study and report on the problem. The study (De Haven, July, 1953) reviewed injuries of 1039 survivors of airplane crashes. Of these survivors, 79.9% had injuries to the head, 6.1% had injuries to the neck (including the cervical spine), 19.8% had injuries to the upper torso (including the dorsal spine) 23.9% had injuries to the lower torso (including the lumbar spine), 15.8% had injuries to the spine, and 59.1% had injuries to the extremities. Thirty nine survivors were not using the safety belt. Of the remaining 1000 survivors, only 9 (0.9%) had dangerous (life threatening) lower torso injuries for which the safety belt could reasonably be considered as a direct cause.

The aircraft involved in the accidents of these early (1942-1952) studies were primarily of fabric-skin covered designs, and the safety belts were usually made of cotton. After the war, the availability of synthetic fibers for use in safety belts of civil aircraft allowed the aircraft industry to adopt a voluntary standard for safety belts which increased the strength of the single occupant belt to 3000 lbs (NAS 802, Approved 1948, Revised 1950).[Note 1] Most of the new aircraft introduced after the war used all metal designs. In a study of accident data obtained during 1953 -1960 in which these new designs predominated, differences from the early studies were noted (Pearson, 1962). Contrary to the earlier findings, seat failure occurred more frequently than belt failure. The curve of belt failure plotted as a function of impact velocity did not accelerate as rapidly as that from the earlier data, whereas seat-failure curves were comparable. When occupant tiedown was effective (no seat or restraint failure) injuries were less severe for the more recent data. Occupants who were wearing shoulder harnesses were least severely injured, although some still received facial and skull fractures. Since structural collapse was not generally extensive for the crashes studied, these injuries were attributed to flailing of the body against injury producing structures within the occupant's environment, even though the shoulder harness was used.

The efforts of the CIR initially involved cooperation with the police departments of several states in order to obtain accident data. The techniques of aircraft crash injury investigations were observed, and began to be applied to automobile investigations. Ultimately, the CIR project was divided into Automotive Crash Injury Research (ACIR) headquartered at the Cornell Aeronautical Laboratory in Buffalo, New York, under the direction of John Moore. Aviation Crash Injury Research (AvCIR), was headquartered at LaGuardia Airport in Flushing, New York until October, 1957 and then at Sky Harbor Airport in Phoenix, Arizona, under the direction of Hasbrook. Major financial support for AvCIR came from the military services, with lesser amounts from the CAA (now the Federal Aviation Administration, FAA), the National Institutes of Health, the NACA (National Advisory Committee for Aeronautics, now NASA, the National Aeronautics and Space Agency), and various independent industry and safety organizations.

AvCIR RESEARCH FOR MILITARY APPLICATIONS.

With most of its support provided by military organizations, the direction of AvCIR's work became more and more directed towards the needs of the services. Between 1955 and 1959, AvCIR investigated 16 military aircraft crashes, 9 transport aircraft crashes, and 4 crashes of small civil aircraft. Evaluations of fixed wing and helicopter aircraft for potential crash injury problems were conducted, and recommendations made for improvements. Work was begun late in 1955 on a Crash Survival Design Manual, which by 1959 contained sections on Survival Design Precepts, Design Tip Sheets, and Engineering Data Sheets (Petry, 1960). Administration of AvCIR was transferred to the Flight Safety Foundation (FSF) in April, 1959, and the name changed to Aviation Safety Engineering and Research (AvSER) in May, 1963. The name change reflected the broad scope of activity which was then being accomplished at AvSER. While crash injury research remained an active area of investigation, AvSER began to direct more of its resources to engineering aspects of crashworthiness, recommending structural airframe improvements, studying crash resistant fuel cells, the effect of fuel gelling agents, and evaluating breakaway fuel tank designs and fire inerting systems etc. An extensive series of controlled crash tests began in 1960 which provided the opportunity for creating a controlled impact environment for evaluating potential improvements in crashworthy designs. There has been no single synopsis of all the accomplishments in these tests. Each test could include studies of many different systems, each of which could be reported in a different forum. Table 1 provides an attempt to list those tests that were identified in the reports listed in the Bibliography.Note 2 Test T-38 was the last test in this series which was conducted by AvSER. Since that time, five additional crash tests, numbered in this same series, have been completed under the sponsorship of the U.S. Army.

The goal of this long range program was to develop and demonstrate practical designs which could be used to improve aircraft crashworthiness. A series of reports discussing various aspects of systems essential for crash worthy aircraft design led to the development of comprehensive design guidance.Note 3 In 1967, these studies and the results of other studies conducted by the Air Force and NACA were consolidated into the "Crash Survival Design Guide" (CSDG)(Turnbow, 1967). This document, for the first time, provided a single source suitable for use as a designer's guide by aircraft design engineers and other interested personnel. The CSDG presented the data, design techniques and criteria which were available in eight areas:

1. Aircraft Crash Kinematics and Survival Envelopes
2. Airframe Crashworthiness Design Criteria
3. Aircraft Crew and Troop/Passenger Seat Design Criteria
4. Crew, Troop/Passenger and Cargo Restraint System Design Criteria
5. Occupant Environment Design Criteria
6. Aircraft Ancillary Equipment Stowage Design Criteria
7. Emergency Escape Provisions
8. Postcrash Fire Design Criteria.

In one of the more significant advances for occupant protection systems, this CSDG presented specific dynamic test procedures for seat and restraint systems, with well defined impact and pass/fail criteria. It also introduced a static test procedure which considered the potential for relative floor/seat deformation, breaking with long standing practice of static strength tests performed on a seat fixed to a rigid test fixture representing an undeformed floor.

While the CSDG presented solutions to specific problems wherever possible, it acknowledged that, because of the lack of specific detailed information, only general philosophy appropriate to the solution of a problem could be given in several areas. As additional data became available, or better techniques were developed, the Crash Survival Design Guide was upgraded and reissued. The 1969 revision (Turnbow, 1969) included major changes in the design and test impact pulses based on accident investigations through 1965, and provided information on energy absorbers. The 1971 revision (Army, 1971) increased design pulses in the lateral direction for helicopters, introduced the Severity Index for head impact, discussed crushable airframe structure for energy absorption, discussed the dynamics of energy absorbing seat/occupant systems, provided new static design and test requirements for seats, revised guidance for restraint systems, provided data on energy absorbing materials for padding, and provided extensive new information on fuel system crashworthiness.Note 4 It was the 1971 revision of the Crash Survival Design Guide that was the basis for the criteria contained in the Army's first standard for aircraft crashworthiness (DOD, MIL-STD-1290(AV), 1974). A greatly expanded (5 volume)

Table 1. AvSER and U.S. Army Crash Tests

Test T-	Test Aircraft	Date	Impact velocity, fps V_r	V_v	V_h	Impact angle, degrees pitch	roll	yaw	Test Purpose	References
1	H-25	22-10-60	62	44	44	0	6L	5L	First test in series. Evaluate seat and restraint systems, fiberglas range extender tank placed in crew seat, and measure crash accelerations.	Turnbow, 1961a, 1961b McCourt, 1961
2	HUP-2	14-6-61	57.3	42.6	43.3	10 U	7 L	11 L	Repeat of T-1 crash environment. Suspended dummy from aircraft ceiling by a standard parachute harness Rubberized fabric range extender tank in crew seat.	TRECOM, 1962 Robertson, 1962
3	H-13	17-6-61	56.6	43.3	35.6	3 U	3 L	35 L	Repeat of T-1 crash environment. Fiberglas range extender tank in right seat, prototype external breakaway fuel tanks.	TRECOM, 1962 Spencer, 1962
4	HUP-2	9-8-61	53.9	42.9	32.6	9 U	7 R	0	Repeat of T-1 crash environment. Experimental troop seats suspended from aircraft ceiling by energy absorbers, Copilot dummy was on energy absorbing seat made of five layers of paper honeycomb, crew restraint attached to airframe structure, one dummy seated on floor.	TRECOM, 1962 Robertson, 1966
5	H-13	3-8-61	56.4	42.8	36.7	0	0	3 L	Repeat of T-1 crash environment. Range extender tank with protective boot on front end located between crew seats. External breakaway fuel tanks.	TRECOM, 1962
6	H-21	29-7-62							Crash fire test with aircraft flown by remote control. 30-bottle ambient air system and temperature measuring system for post crash fire environment measurements.	TRECOM, 1963
7	H-21A	12-9-62	62.5	40	48	3 U	4 L	0	Aircraft flown into crash by remote control into crash. Post-crash fire inerting system installed. Crew seat, honeycomb seat, troop seats with energy absorbing leg, commercial helicopter seat and litters tested.	TRECOM, 1963 Weinberg, 1963 Reed, 1964 Turnbow, 1963b Robertson, 1963 Schamadan, 1963

Table 1. AvSER and U.S. Army Crash Tests, continued.

Test T-	Test Aircraft	Date	Impact velocity, fps V_t	V_v	V_h	Impact angle, degrees pitch	roll	yaw	Test Purpose	References
8	H-21A								Postcrash fire test	TRECOM, 1964
9	H-21A	18-4-63	89.3	52.5	66	1 U	2 L	0	First test with live animal, troop seat with energy absorbing leg Experimental litter restraint:	Weinberg, 1965a Weinberg, 1966
10	H-21A								Postcrash fire test	TRECOM, 1964
11	H-21A								Postcrash fire test	TRECOM, 1964
12	H-21A	5-10-63	40	11	38	3 U	2 L	5 R	Aircraft flown into crash by remote control. Troop seat with energy absorbing leg, fuel cell test	Weinberg, 1965a Robertson, 1966a
13	H-21A	22-10-63	52.2	36.8	38.6	5 U	0	0	Drop test. Troop seat with energy absorbing leg, fuel cell test	Weinberg, 1965a Robertson, 1966
14	H-21A								Seat, Gel Fuel, Fuel Tank Evaluation	
15	TC-45J								Unmodified airplane guided by rail to pole barriers and 30° slope hill. Structural response to crash.	
16	C-45		144					35 R	Airplane guided by rail to pole barriers and 30° slope hill. Structural impact data: Wing tank impact:	Reed, 1966 Robertson, 1966
17	H-34	10-3-65	59	42.4	41				Drop Test. Fuel containment with various tank construction:	Robertson, 1966
18	H-21	17-2-65	59	39.3	44				Drop Test. Fuel containment with various tank construction: Cargo restraint:	Robertson, 1966
19	C-45		140					35 R	Airplane guided by rail to pole barriers and hill. Modified aircraft nose structure: "Tough Wall" wing tank impact:	Reed, 1966 Robertson, 1966
20	XH-40		59.4	40	44	10-15 D	5 L		Drop test. Experimental litter system:	Weinberg, 1966

Table 1. AvSER and U.S. Army Crash Tests, continued.

Test T-	Test Aircraft	Date	Impact velocity, fps V_r	V_v	V_h	Impact angle, degrees pitch	roll	yaw	Test Purpose	References
21	OH-4A	13-5-65	25	25	0	0	0	0	Vertical Drop Test on soil. Airframe structural performance, Postcrash fire protection, seat, restraint, and injury analysis:	Turnbow, 1966
22	OH-4A	3-6-65	48.9	25	42	0	0	0	Drone crash test on soil. Airframe structural performance, Post crash fire protection, seat, restraint and injury analysis:	Turnbow, 1966
23	H-34	9-9-65	59						Drop test. Fuel containment with experimental tanks:	Robertson, 1966
24	C-45	12-8-65	101					35 R	Airplane guided by rail to pole barriers and 30° slope hill. Experimental fuel tanks: Increased upper cabin commpressive strength to reduce bending:	Robertson, 1966 Reed, 1966
25	OH-5A	-3-66	25	25	0	0	0	0	Crash survival, Crew protection	
26	TC-45J	-5-66							Emulsified Fuels Evaluation	
27	YH-41								Postcrash fire, JP-4	
28	YH-41								Emulsified fuel test	
29	TC-45J								Postcrash fire, JP-4	
30	TC-45J								Emulsified fuel test	
31	UH-1	23-2-68	84.2	23	81	12 D	0	3 L	Radio controlled flight into soil. Crash resistant flammable fluid system:	Robertson, 1968
32	T-33A								Emulsified fuel test	
33	T-33A								Emulsified fuel test	
34	UH-1D/H		29.9	29.9	0	½ D	0	2 R	Drop test to concrete pad. Structural analysis and computer model:	Gatlin, 1971
35	UH-1D		44	44	0	2 D	0	0	Crashworthy fuel system test	Cook, 1971

Table 1. AvSER and U.S. Army Crash Tests, continued.

Test T-	Test Aircraft	Date	Impact velocity, fps V_x	V_y	V_b	Impact angle, degrees pitch	roll	yaw	Test Purpose	References
36	UH-1D		42.5			25	10 R	45 L	Crashworthy fuel system test	Cook, 1971
37	UH-1D		47	38.9		7 U	8	0	Crashworthy fuel system test	Cook, 1971
38	UH-1D			23	18.6	1 D	10 R	90 L	"KRASH" computer modeling	Wittliln, 1973
39	CH-47C	6-3-75	49.5	39.5	28.9	10 U	1 R	0	Drop test at NASA LaRC. Energy absorbing troop seats, side facing troop seat, armored and unarmored crew seats, cargo tie down loads:	Singley, 1976
40	CH-47	4-8-76	51.9	43.5	28.3	8.7 D	0	0	Drop test at NASA LaRC. Structural, cargo restraint, aircrew inflatable restraint system: KRASH model analysis:	Schulman, 1977 Burrows, 1978 Badrinath, 1978
41	YAH-63	7-8-81	60.1	48	36.2	9.25 U	0.5 L	0	Drop test at NASA LaRC. Inflatable crew restraint system, crashworthy crew seats, flight incident recorder and crash position locator, emergency locator transmitter: Structural simulation and analysis: Inflatable restraint system:	Smith, 1986 Berry, 1983, 1986 Domzalski, 1984b
42	Bell D-292	-8-87	49.1	41.4	26.4	15 U	14.5R	0	Composite airframe crashworthiness, landing gear, seat energy absorption	
43	Sikorsky S-75	-9-87	39	30	0	10 U	10 R	0	Composite airframe crashworthiness, landing gear, seat energy absorption	

CSDG was published in 1980 (Simula, 1980). The latest version (at this time of writing) was issued in 1989 (Simula, 1989) also consists of five volumes:

Volume I - Design Criteria and Checklists
Volume II - Aircraft Design Crash Impact Conditions and Human Tolerance
Volume III - Aircraft Structural Crash Resistance
Volume IV - Aircraft Seats, Restraints, Litters, and Cockpit/Cabin Delethalization
Volume V - Aircraft Postcrash Survival.

Careful study of these reports is advisable for anyone seriously interested in crashworthy aircraft design techniques.

AvSER CRASH TESTS OF TRANSPORT AIRPLANES.

Although the major programs conducted by AvSER during the 1960's were funded by the military services and directed towards ultimate military applications, AvSER also continued to work on civil crash problems. In 1963, AvSER was awarded a contract by the FAA to conduct two full scale crash tests using large transport type aircraft. The objectives of this program were to:

1. Measure the dynamic crash forces imposed on two large transport-type aircraft during a typical takeoff or landing accident;

2. Correlate the visual analysis of fuel tank rupture and fuel spillage patterns with a measurement of wing accelerations and fuel pressures;

3. Evaluate new methods of fuel containment, such as gelled fuel and honeycomb tanks in a typical crash environment;

4. Evaluate the performance of the latest designs for:
   a. three-place seat configurations;
   b. two-place forward facing seat configurations;
   c. two-place rearward facing seat configurations;
   d. galley and auxiliary equipment installations;
   e. infant restraint installations.

5. Evaluate the effects of seat spacing, seat breakover features and "jackknifing" of occupants in the crash environment.

6. Evaluate cargo restraint (in cooperation with the Society of Automotive Engineers Committee on Cargo Restraint).

7. Evaluate experimental flight deck seats (in cooperation with the U.S. Navy).

These tests still provide us with the most useful data available for understanding the crash environment in severe, but survivable crashes of large transport aircraft.[Note 5]

The first test, conducted in April, 1964, involved a Douglas DC-7 aircraft (Reed, 1965). The aircraft, under its own power, was guided by a 4000 foot rail to the prepared crash site. It impacted landing gear barriers at over 139 knots, knocking off the landing gear. All four propellers next struck propeller barriers, breaking the propellers and engine mounts. The aircraft wings next encountered barriers which cut off the right wing tip and ruptured a main fuel tank which was filled with simulated fuel, and crushed the right wing leading edge back to the forward spar between engines 3 and 4. The aircraft then struck an eight degree hill in a level pitch attitude with negligible roll and yaw. During this impact, the fuselage broke at approximately station 300 and failed both wings at the wingroots. The aircraft passed over the summit of the 8° hill, then impacted a second hill which had a 20° slope. The nose of the aircraft was pitched downward at about 10° at that impact. The aircraft bounced over the summit of the second hill, and came to rest on the backside of the hill 860 feet from the point of contact with the main landing gear barriers. The main fuselage came to rest at a 45° angle to the flight path and rolled over on its left side. Several small fires occurred when the aircraft broke up but were easily extinguished after the test. Due to a failure of the onboard data recording system, acceleration and force records were obtained only from the cockpit. The experimental pilot seat (a nylon net seat) failed completely at the floor tracks. The experimental energy absorbing copilot seat was damaged by intrusion of the lower and forward cockpit. Two standard two-place DC-7 passenger seats in the forward cabin were torn loose from their mounting during the crash. One seat, occupied by a child dummy which was restrained by a vest type restraint, remained in place although it was damaged due to vertical load. It appeared that the child dummy had been subjected to considerable flailing. Typical forward facing seats installed over the wing spar remained in place and restrained their dummy occupants. Forward seat backs broke over in the forward direction, and showed indication of impact by the dummy occupants seated behind them. The seat backs on the U.S. Air Force rearward facing seats installed over the wing all failed during the crash, allowing the dummy occupants to slide out of the seats, even though the seat belts remained fastened. Pre-inflated air bag restraints and seat belts were provided in two standard seats placed aft of the galley on the left side of the fuselage. The dummy occupants of the seats were retained in position, even though the airbags were damaged or allowed to move out of position as a result of failure of the forward seat back which was supporting the bag. Dummies seated in a standard seat in the aft cabin remained in place, even though the belt attachment for the aisle seat failed. The head of the dummy in that seat severely impacted the seatback in front, causing the head to separate from the neck. The belt attachments in the standard DC-7 side facing lounge seat failed and did not retain the dummy occupant. Accelerometers on the floor at the copilot seat location indicated peaks of 27 G longitudinal and 31 G vertical during the impact with the 8° slope, 47 G longitudinal and 36 G vertical during impact with the 20° slope, and +25 G to -66 G longitudinal and +33 G to -47 G vertical during the final impact on the backside of the second hill.

The second test, conducted in September, 1964, used a Lockheed Constellation Model 1649A aircraft (Reed, 1965b). Wing fuel tanks were filled with colored water, except for the mid wing tanks which were filled with gelled water. A special 55 gallon fuel tank, located in the wheel well of the No. 2 engine nacelle, provided fuel for the test run. As before, the aircraft was accelerated, under it's own power, along a 4000 ft guide rail to the prepared impact site. It impacted the landing gear barriers, breaking off all landing gear and causing the No. 2 engine to roll under the left wing, at a velocity of 112 knots. After passing over the gear barriers, the aircraft dropped in a slightly nose down attitude. Propellers on Nos. 1, 3 and 4 engines struck the earth and disintegrated. At this point, visible rupture of the wing structure adjacent to the engine nacells began. The left wing struck the earthen wing barrier and began to separate from the fuselage. The right wing impacted pole barriers 25 feet from the tip and between engines 3 and 4. The nose of the aircraft then contacted the ground at the base of a 6° slope hill, and slid into the hill. No major breakup of the fuselage occurred during this impact. After passing the crest of the 6° slope, the airplane rotated to a slight nose down attitude, and then impacted a 20° slope. This produced two fuselage breaks; aft of the cockpit and aft of the galley located in the rear of the aircraft. The aircraft came to rest on the second slope nearly upright and aligned with the original path. Small fires, fed by engine oil, hydraulic oil, and the small amount of fuel remaining, were quickly extinguished. Most instrumentation functioned properly, but on-board cameras did not operate.

The forward section of the fuselage was crushed almost to the level of the cockpit floor, which was deformed upward and twisted aft of the crew seats. The fuselage broke across the forward cabin just aft of the main door. Vertical space in the cargo hold was reduced from the normal 3 feet to only 6 inches at the fuselage break. Further aft, several floor panels were broken up, and numerous failures occurred in the lower structural members of the cargo hold. The floor aft of the wing had been strengthened for seat experiments and remained flat and intact. The floor bent downward at the aft fuselage break, but did not part. Data indicated that the maximum floor acceleration reached 25-30 G in the longitudinal direction, and over 25 G in the vertical direction in the cockpit during impact with the 20° slope. Vertical accelerations of 15-20 G and lateral accelerations of 5 G were measured throughout the cabin, with peak lateral acceleration of about 10 G measured in the cockpit. Duration of these impact accelerations were from 0.1 to 0.2 seconds.

Helicopter type crew seats were provided by the U.S. Navy for installation in the cockpit on reinforced floor attachments. The aft attachment of the pilot and copilot seat failed by outward bending of the lips of the fittings over the floor track and the seats were damaged but remained in place, secured by the forward fittings. Both seat pans bent downward and contacted the floor. Seat backs were bent forward due to forces from the shoulder harness. Helmets remained in place on the dummies heads, but indicated severe impact with the cockpit interior. A third crew seat, located in the berth area of the cockpit, became detached from the floor tracks because of failures of the lips of the seat attachment fittings. The nose gear was embedded under the fuselage just beneath this seat location, and may have caused high localized floor loading which contributed to the failures.

Three standard two place passenger seats were installed at a 32 inch seat pitch in the forward passenger cabin, with the center seat row occupied by two anthropomorphic dummies restrained by lap belts. The aft seat next to the wall was occupied by a dummy restrained by a lap belt and single diagonal shoulder strap which incorporated an energy absorbing reel. A child dummy was restrained in the aft inboard seat by a harness-type child restraint system which was attached to the floor by a single strap that passed between the seat back and seat pan. The forward seats were intended to provide a realistic environment ahead of the dummies in the center seat row, and were unoccupied. The forward and center seat rows remained in place during the crash. The aft seat row was released from the floor track during the crash because the floor track locks had not been installed, and rotated backwards, coming to rest on its back. The forward seat was deformed laterally inward, due to loads applied by the deformed fuselage side wall. The center seat was not laterally deformed, but both front and aft lateral seat frame tubes were bent downward. The dummy seated next to the wall was still in place with feet and legs in a normal riding position, and bent forward so that his chest was resting on his thighs, and his head had contacted the seat back of the forward seat. The dummy seated next to the aisle remained in his seat, bent forward, head in the aisle and legs extended under the forward seat. Examination of the forward inboard seat back indicated that contact between the dummy and the seat back was very slight.

Two specially designed cargo pallets, each carrying 2000 pounds of cargo, were attached to reinforced floor structure just behind the forward passenger seats. Following the test, the fuselage section containing the cargo experiment was generally intact, even though accelerations of 20 G vertical, 10-20 G longitudinal and 5-10 G lateral were experienced. No failures occurred in either of the cargo tie down systems.

Two standard three passenger seats, at a 34 inch pitch, were installed on reinforced floor on the right side of the aircraft over the center wing section. Three anthropomorphic dummies were restrained in the aft seat by lap belts. The unoccupied forward seat was intended to provide a realistic environment for the aft seat passengers. All three dummies were restrained in their seats throughout the test. The dummies in the outboard and center seat positions contacted the seat backs in front of them, slightly buckling the perforated sheet metal back pans.

Two rear facing military (Air Force) passenger seats, one two-place prototype seat and one three-place production seat, were installed on reinforced floor structure on the left side of the fuselage in the center wing section. Both seats withstood the crash with no visible deformation or failure. All five dummy occupants remained in their seats and in position.

Two U.S. Navy litters were installed on the right side of the aircraft, aft of the wing. These litters were attached to the main cabin floor and fuselage wall structure, and were occupied by anthropomorphic dummies. The litters remained intact throughout the crash, with no permanent deformation. Both dummies were restrained in place, although they moved forward enough to cause 1/4 inch deep heel marks in the rigid foam blocks placed at the forward end of each litter.

The galley section was loaded with 440 pounds of simulated equipment placed in twenty food tray containers, and six empty beverage containers were in place. The galley was not severely disarranged by the crash and the tray containers and their contents remained in place, but the beverage containers were thrown from the galley into the main cabin. The unoccupied cabin attendants folding seat opened during the crash, partially blocking the path through the galley door.

The flight engineers seat had been removed from the cockpit and installed on reinforced floor on the right side of the aft fuselage as a side facing seat. An anthropomorphic dummy was restrained in the seat by a lap belt. Although the seat remained attached to the floor and sustained no gross failure, the lap belt allowed the dummy to move laterally (towards the front of the aircraft) and impact the galley partition located 24 inches ahead of the seat. The dummy moved partially off the seat, and the dummy's right leg swung about 35 degrees to the dummy's right.

Two standard first class two-passenger seats were installed at 36 inch pitch near the left side of the aft cabin. The seats in the aft row were occupied by anthropomorphic dummies restrained by lap belts. The unoccupied seats in the forward row were intended to provide a realistic environment for the aft seat passengers. Both of the seats remained attached to the floor. The bolt holding the left side of the lap belt to the seat failed on the aft inboard seat, allowing the dummy to slide forward, jamming both legs under the forward seat. The dummy in the aft outboard seat was found with its face against the forward lower seat back and both legs jammed under the forward seat up to the knees, even though the lap belt was still attached. The tubular frames of the aft seats broke and allowed the forward edges of both seat bottoms to deflect downward to the floor.

The standard folding cabin attendant seat furnished at the rear of the aircraft was occupied by a small (130 lb) anthropomorphic dummy, restrained by a lap belt and dual shoulder belts which were attached to the lap belt approximately 6 inches on either side of the buckle. Although the shoulder harness and lap belt remained intact and attached, the dummy submarined until the lap belt was around it's chest. The attachment of the seat back to the bulkhead failed, and the right front seat leg was buckled inward during the crash.

Children's dolls were placed in two airline type bassinets, one restrained by cross-over straps, and the other restrained by a nylon net stretched over the bassinet. The bassinet with the nylon net was attached to brackets in the forward wall of the cloak closet located in the tail. The other bassinet was placed on the floor of the closet, with its side against the forward wall. Both bassinets retained the dolls and remained in position, although the bassinet on the floor turned completely over. Other experiments in this crash included ejection of a flight recorder and a locator beacon, several different interior lighting and emergency exit lights, and a hazardous cargo shipping container test.

NACA STUDIES.

De Haven had repeatedly urged that crash tests be made at controlled speeds using several old model airplanes to reproduce the distortion and structural collapse found in his field investigations, so that the forces involved in the crashes could be measured and documented on film (De Haven, 1950). The National Advisory Committee for Aeronautics responded by initiating a comprehensive study of airplane crash problems at the Lewis Flight Propulsion Laboratory. This program, and a subsequent program conducted at the Langley Research Center provides the available data for the impact environment for small and mid-sized fixed wing airplanes. The analysis of criteria for seat design provided one of the first analytical studies which demonstrated the benefit of energy absorption on occupant protection in a crash. The report which summarized the literature pertaining to human tolerance to impact has been used as a basis for many seat designs. Consequently, the program warrants a fairly detailed review.

Black (1952) described a "ground-to-ground" technique for guiding an aircraft, under it's own power, along a rail to a crash site prepared with barriers for shearing off landing gear and propellers, rupturing fuel tanks and simulating ground impact. This technique could provide better control over the crash conditions than "air-to-ground" methods. Using this technique, surplus military transport and cargo airplanes were crashed to study aircraft crash-fire problems.

Eiband and Simpkinson (1953) reported on acceleration and harness loads measured in three crash tests of steel-tube, fabric covered, tandem two-seat light aircraft. Using the techniques described by Black, aircraft were crashed into an earthen barrier, compacted to represent undisturbed clay turf soil. The front face of the barrier was sloped at an angle of 55°, and the barrier was placed at a 66° angle with the path of the aircraft, so that the aircraft impacted the left wing first. An Air Force parachute dummy was placed in the front seat, and an experimental Air Force anthropomorphic dummy was in the rear seat. The parachute dummy did not simulate the human body except for mass distribution, while the anthropomorphic dummy used elastic shock cord to simulate muscles and sponge rubber to simulate flesh and skin, and was considered a reasonable replica of the human body in both mass distribution and tissue resilience.

For tests at 60 and 42 miles per hour impact speed, the front dummy was restrained with a standard 2-inch wide seat belt attached to the front seat of the airplane and the rear dummy was restrained by a military seat belt and shoulder harness attached to the airframe. The belts were statically tested by applying a straight pull lengthwise along the belt until failure. The 2 inch wide belt sustained a 1515 pound tensile load before failure occurred. In this test, the webbing failed because of the cutting action of the serrations of the buckle clamp. In a test using a fixture which simulated the curvature of the body in the pelvic region, including folding together of the belt edges across the pelvic region, the belt failed at the same loads and with the same type of failure, thus indicating that belt failures were not caused by unequal stress distribution resulting from flexion of the torso over the seat belt. The three inch military seat belt assembly was tensile tested in a straight pull, and failed under a load of 2620 pounds. Failure was caused by cutting of the webbing by the adjusting buckle, but the buckle hook was also found to be broken after the test. The shoulder harness assembly was tensile tested while held in a "Y" configuration, and failed under a load of 4725 pounds when the webbing on one of the shoulder belts was cut by the adjusting buckle. The front seat was removed for one test at 47 miles per hour, and the anthropomorphic dummy in the rear seat was restrained only by the 2 inch wide seat belt, which was backed up by the 3 inch wide belt installed with 8 inches of slack.

The maximum longitudinal deceleration, measured on the floor of the aircraft at the rear seat position in each test, was between 26 and 34 G. It did not change appreciably with impact speed, probably due to progressive crushing of the fuselage. This was indicated by an increase in the duration of deceleration from 0.023 to 0.070 seconds. Vertical and lateral accelerations were reported for the 42 mph crash. Despite the asymmetrical crash configuration, the 6 G peak lateral accelerations did not indicate any tendency to predominate in either direction. Peak vertical accelerations of 6 G were reported. While fuselage crush and head impact were problems for the front seat occupant, it was concluded that the decelerations in these tests were tolerable for a rear seat occupant, restrained by a seat belt and shoulder harness. To avoid injury producing contact when only seat belt restraint is used, it was recommended that the space in front of the occupant should remain free of obstacles for a distance approximately equal to the length of the torso from the hips to the top of the head plus the seat belt elongation.

Acker, et al. (1957) reported on accelerations measured in five crash tests of surplus single place, low wing, twin jet FH-1 fighter aircraft of conventional construction. Three tests simulated unflared landings at 18°, 22° and 27° impact angles (angle between airplane trajectory and ground), one test represented a cart wheel accident, and one test represented a ground-loop crash. A 200 pound anthropomorphic dummy, equipped with a life preserver, seat-pack parachute, and helmet was restrained in the pilot seat by various types of safety harnesses. Impact velocity for all tests was about 112 miles per hour.

Restraint in the 18° impact crash was provided by a standard military 3 inch nylon lap belt and a 1.75 inch cotton shoulder harness. The one shoulder belt broke in that crash, so the shoulder harness was replaced by a similar harness made of synthetic (Dacron) material. This was used in the 22° impact crash and in the cart-wheel and ground-loop crashes. In the 27° crash test, an experimental harness developed by Stapp (1951) was used. This harness consisted of two layers of 3-inch nylon webbing stitched together for the harness and lap belt. In addition, two pieces of single thickness nylon webbing were used for thigh straps which passed under the dummy's buttocks and came up the crotch and over the thighs. All straps fastened together at the lap-belt buckle. All restraint systems were fastened to a rigid aluminum armor plate bulkhead just behind the pilot's seat.

In the 18° and 27° impacts, the longitudinal axis of the aircraft and the flight path angle were parallel at the moment of impact, but in the 22° impact, the longitudinal axis of the aircraft tipped upward 9° with respect to the flight path at the moment of impact. In the 18° and 22° impacts, the aircraft bounced into the air after the initial impact and flew an additional 200 feet before again impacting the ground and coming to rest. The aircraft stopped within its own length in the 27° impact.

For the ground loop crash test, only the left landing gear was ripped off by an abutment, so that the left wing tip dropped to the ground, struck an earthen bank, and rotated the airplane rapidly until the right wing impacted the mound and sheared off the remaining nose and right wheel struts. The airplane then slid tail first until it struck a second earthen bank, bounced into the air tail first, and slammed down on its belly, coming to rest 50 feet behind the second bank. The cartwheel crash was created by rolling the airplane along a 85 foot long twisted ramp at the crash end of the runway before it left the guide rail. The ramp rolled the airplane until its left wing was at a 30° angle with the horizon. The left wing then struck an earthen bank located 10 feet beyond the end of the ramp, which cartwheeled the airplane. As it tumbled it struck the ground nose first, then impacted the left wheel, destroying the left landing gear, then landed on its belly and slid to a stop.

While local structural accelerations of up to 140 G were measured as various components impacted the ground in the various tests, the accelerations at the cockpit floor or the center of gravity of the airplane was considerably less. In the ground loop crash, the peak longitudinal acceleration on the cockpit floor was only 4 G initially, 3 G during the slide and 9 G during the rearward impact with the second earthen bank. In the cart-wheel crash, peak longitudinal accelerations of 9 G occurred when the wing tip and fuselage dug into the ground. Impact angle was found to influence the severity of the crash. Peak accelerations at the center of gravity of the airplane in the 18°, 22° and 27° landing crashes and the data for the initial 4° impact of the ground loop crash were combined as shown in Figure 3. From these tests, it was concluded that an adequately restrained pilot could withstand greater longitudinal accelerations than the cockpit structure could transmit before it collapsed, but that human tolerance to normal accelerations was exceeded in all the unflared landing crashes.

Accelerations in impact tests of transport airplane crashes were discussed by Preston and Pesman (1958). These experimental crashes simulated takeoff and landing accidents which generated moderate fuselage damage with three types of airplanes. Surplus C-46 airplanes represented twin engine, low wing transports having pressurized cabin type construction, Lockheed Lodestar airplanes represented twin engine, low wing transports having unpressurized cabin construction, and C-82 airplanes represented twin engine, high wing transports having unpressurized cabin construction. The tests made in this series and the basic results from the tests are summarized in Table 2. To compare the accelerations of the various crashes, the recorded data were corrected to a common impact speed of 95 miles per hour by assuming that the maximum acceleration resulting from the first impact of the airplane with the ground varied directly with the initial momentum and thus with the initial velocity. The results of this analysis are shown in Figure 4. It was also observed that, for the low wing pressurized airplanes, the severity of impact in the direction normal to the longitudinal axis of the aircraft decreased as the distance from the impact point increased, but that the severity of impact in the longitudinal direction was less in the mid cabin, as shown in Figure 5. It was concluded that the location of the wing is important in reducing both the degree of fuselage crushing and the acceleration that result from a crash. Conclusions regarding the selection of design accelerations for the seats and their attachments were not made, because the crashes of the study were not severe enough to indicate the maximum strength of the pressurized transport airplane. Even though a maximum of 20 G was recorded on the fuselage floor in the 29° test, only minor damage to the fuselage resulted.

These experimental crash tests led naturally to considerations of occupant injury and injury protection systems. Pesman and Eiband (1956) studied the data from the full scale experimental crashes to determine how impact injuries occur and how the chance of such injuries could be reduced. They considered the hazards of being crushed, being struck by "missiles" (unrestrained objects in the cabin), striking objects as a result of belt, seat structure/attachment failure or flailing about, and being injured by the crash decelerations.

Their test data indicated that if the angle of impact and impact speed are great enough, any airplane will crush, and the survival under such circumstances would be improbable. As the angle of impact was decreased, and if the airplane had a stronger floor structure located well above the airplane's belly, then the occupied zones were less likely to be crushed. In one crash test of a cargo airplane, the weak understructure of the nose crumpled until the floor of the crew compartment was reached. The strong floor prevented further crumpling. Instead, the crew compartment hinged upward, lifting at the front and hinging at a point near the wing's leading edge. This action lifted the compartment so that it was not in a direct line between the main mass of the airplane and the ground. It was then not in the direct line between the main mass of the airplane and the ground, and consequently was not crushed. The authors suggested that the hinging action be deliberately emphasized when designing the aircraft structure. However, they cautioned that the fuselage framing should be designed so that when bending in a crash, either from forward or sideward loading, the fuselage would not collapse inward and crush or entrap occupants in that area.

The problems of missiles included an escape hatch which dislodged during a test and impacted a dummy seated in a rearward facing seat in the front of the cabin, propeller blade fragments which penetrated the fuselage, and nose wheel struts which penetrated the floor of the cabin after being torn off early in the crash sequence. The authors suggested that the hazards of both landing gear and propeller fragments as missiles could be reduced by locating the baggage holds, the galley, the coat rack and toilet compartments in the usual paths of these missiles.

Flailing, where the dummy moves forward about the seat belt until his chest hits his thighs and his head snaps down, was observed in the tests. The authors referenced

Table 2. Floor Accelerations and Crash Environment in NACA Tests of Twin Engine Transport Airplanes.

Aircraft Type	Impact angle, degrees	Impact velocity miles/h	Distance from airplane nose, inches		Aircraft Floor Acceleration					
					Longitudinal		Normal		Lateral	
			Impact Point	Accel-erometers	Peak G	Time, seconds	Peak G	Time, seconds	Peak G	Time, seconds
Low wing, Pressurized	5	81	605	270	2.5	0.190	2.5	0.265		
	15	93	80	250	10	0.120	15	0.095		
				360	11	0.122	10	0.075		
				485	7	0.125	10	0.150		
				680	9	0.125	8	0.170		
	29	97	30	185	20	0.145	25	0.105-0.175		
				335	22	0.145	18	0.135		
				490	20	0.150	12.5	0.160		
				685	17	0.155	10	0.195		
Low wing, Unpressurized	[illegible]	87	108	243	3.5	0.255	9	0.275		
				312	3.5	0.260	9	0.275		
		63	172	243	7	1.653	40	1.653	7	1.653
				312	7	1.680	28	1.680	17	1.680
	16	109	72	243	15	0.195	18	0.180		
				312	13	0.185	16	0.215		
High wing, Unpressurized	4	95	156	138	6	0.150				
				140			12	0.030		
	16	31	56	340	15	0.070				
				341			10	0.300		

research performed by Dye (1953) which indicated that a human skull striking a solid surface with a kinetic energy of 600 inch pounds would be fractured. Since the human head weighs about 10 pounds, a head impact velocity of only 18 feet per second could be hazardous. In their crash tests, they measured dummy head motion of about 67 feet per second when the dummy's chest impacted his knees, with an energy almost 14 times that required for skull fracture. To reduce this hazard, the authors note that the seat backs in several contemporary aircraft were hinged to swing forward or were made of easily deformed metal.

Referencing the research of De Haven and Stapp, the authors conclude that humans can tolerate deceleration loads of 45 G perpendicular to the spine, and 20 G compressive load parallel to the spine if adequately supported. They also suggest that additional restraining harnesses to keep the spine in proper alignment may hold the occupant in a better position to withstand vertical blows.

Pinkel and Rosenberg (1956) applied the crash data obtained in the NACA tests to seat design. They observed that the crash measurements showed periods of high deceleration lasting for several tenths of a second separated by longer time intervals during which the deceleration was below 3 or 4 G's, and that seat failure usually occurred in response to the short-duration high-deceleration phase of the crash. Their study of airplane deceleration records obtained on crash tests of cargo and transport airplanes suggested that the deceleration pulse was made up of a base pulse and a superimposed secondary pulse of the type shown in Figure 6. The values of impact pulse components given in Table 3 were considered to be quite severe from the standpoint of the seat, but were consistent with crash measurements. The lower deceleration suggested for the cargo airplane was attributed to the fact that the fuselage structure of the high wing cargo airplane used in the tests was "soft", so that the deceleration produced by ground-plowing and tearing of the soft structure was relatively modest. The data in this table were considered representative of vertical deceleration and deceleration pulses acting in the front to rear direction along the longitudinal axis of the airplanes. Lateral and rearward decelerations were assumed to have magnitudes equal to 75 and 50 percent, respectively, of those shown in the table with the same time durations, with a corresponding reduction in airplane velocity.

Table 3. NACA Recommended Design Values of Longitudinal Deceleration Pulses for Transport Airplanes.

	Transport				Cargo			
First Crash Deceleration								
Velocity change, f/s	50	80	130	130	50	80	130	180
Primary Pulse								
Maximum G's	12	18	20	20	4	8	10	10
Pulse Duration, s	0.20	0.20	0.25	0.30	0.50	0.38	0.46	0.58
Rise Time, s	Sine	0.06	0.045	0.03	Sine	0.10	0.08	0.06
Secondary Pulse								
Maximum G's	10	15	20	25	7	10	12	15
Pulse Duration, s	0.02	0.03	0.04	0.03	0.06	0.04	0.04	0.03
Second Crash Deceleration								
Primary Pulse, G's	9	9	7	1	4	4	3	1
Secondary Pulse G's	8	7	7	1	6	5	4	1

By modeling the seat as a simple, single degree of freedom linear elastic system responding to the short-duration decelerations, they found that there was a performance range where the system could amplify the crash deceleration rather than just transmitting the deceleration magnitude without change or attenuating the deceleration to transmit a lower magnitude to the occupant. This simple model was accurate as long as the seat operated as a linear elastic system, i.e., the energy of the crash was not sufficient to stress the seat beyond the linear elastic limit. If the energy in the crash impact is sufficient to exceed the elastic limit of the seat, the seat should be capable of appreciable deformation beyond the elastic limit with high "holding force" maintained to the breaking point as shown in Figure 7. This figure also shows two undesirable seat-deformation modes. Curve A shows high seat-holding force beyond the elastic limit, but a small allowable deformation before breaking. Such a curve would represent a seat whose members being deformed are brittle, or one in which the entire load passes through a single structural element which is the weak link in the stress chain. Curve B shows a seat-holding force that declines rapidly with deformation beyond the elastic limit. This performance is often representative of efficient, lightweight structures. The energy absorption capability represented by both of these curves can be insufficient to prevent destruction of the seat if it is stressed beyond the elastic limit.

Pinkel and Rosenberg considered that the three principal qualities of a seat that relate to its ability to hold a passenger through severe deceleration pulses were the seat natural frequency, its static strength, and its ability to absorb energy in deformation beyond the elastic limit. They then used linear super-positioning to determine the performance of an elastic seat system to the primary and secondary pulses shown in the Table for the 80 foot per second transport airplane first deceleration. They found that the maximum seat deceleration would vary between 40 and 48 G (depending on seat natural frequency which was assumed to range between 2 and 16 Hz), in response to a peak airplane deceleration of 33 G. This analysis also confirmed that energy absorbing requirements past the yield point of the seat would decrease as the seat strength increased. For example, a seat with a static design strength of 20 G might have to absorb about 3000 foot-pounds of energy (with 0.75 foot displacement) while a seat designed for 28 G would have to absorb only about 900 foot-pounds of energy (with 0.16 foot displacement) to avoid destruction in the 33 G, 80 foot per second impact.

As a result of this analysis, they concluded that while there seemed little to gain in a choice of seat natural frequency, some advantage may favor lower seat frequencies for airplane decelerations where the secondary pulse is significantly larger in magnitude than the base pulse and has a short duration. This would be important in seats designed to hold passengers in decelerations that approached the human tolerance (injury) levels, where a low frequency seat (which corresponded in their analysis to a seat with low static design strength) might keep the passenger deceleration within the tolerance limits.

This concept was evaluated by building experimental seats which provided two ranges of natural frequency in the same seat assembly. A variety of seats having the general force/deflection characteristics as shown in Figure 8 were built for testing in horizontal impacts. These "duplex" seats were supported by a pre-stressed cylindrical elastic pedestal. Basic structural stiffness provided the initial high slope force/deflection characteristic. When the pre-stress level of the pedestal was reached, the elastic cylinder deformed to provide the second low slope deflection. This seat and a conventional rigid passenger seat were subjected to impacts of 30 G and 22 G, respectively, on a swing type test facility. A 200 pound dummy served as seat occupant in both tests. The results of these tests are shown in Table 4.

Table 4. Results of Tests with NACA Duplex Seat

Seat Type	Longitudinal Deceleration, G			Ratio of Dummy G to Floor G	
	Test fixture floor	Dummy			
		Hips	Chest	Hips	Chest
Duplex Seat	30	20	12	0.66	0.4
Rigid Seat	22	27	30	1.23	1.36

Test seats having force displacement characteristics shown in Figure 9 were built for vertical impacts. An energy absorber, consisting of three concentric cylinders made of corrugated aluminum was placed between the seat cushion and the seat frame. This seat, occupied by a 200 pound dummy, was exposed to a floor deceleration of 40 G on the swing platform, and limited deceleration in the dummy's hips to 20 G.

Pinkel and Rosenberg conclude their report on seat design by discussing several matters of concern:

- Slack in the seat or restraint system will have unfavorable consequences. When no slack is present, the maximum seat deceleration will never exceed twice that of the airplane. However, this ratio will increase if slack is present. For example, 3 inches of slack in a system having a natural frequency of 17 Hz will generate a seat deceleration 3.5 times that of the airplane. Slack can be caused by loose restraints, restraints that slip or stretch under low loads, and soft or deep seat cushions. A proper seat pan cushion should compress completely under the weight of the occupant and bring his buttocks substantially in contact with the seat pan.

- The (then) current practice of fastening seats to the airplane fuselage wall and the floor exposes the seat to failure when the airplane structure between the fastening points distorts during a crash and changes the distance between the points.

- Floor structure that flexes under load can seriously modify the effective seat natural frequency and reduce the ability of the seat to support the passenger.

- Higher landing and takeoff speeds increase the probability that more than one principal deceleration pulse will be experienced in a crash. The designer should consider residual strength of a seat following the crash deceleration pulse for which the seat is designed. The higher the landing speed, the higher the residual strength should be. Second crash deceleration pulses for airplanes having a landing speed of 180 feet per second were given in Table 3. Pulse durations and rise times should be the same for the first and second decelerations. The residual strength of the seat should be high enough to serve in a second deceleration whose primary and secondary pulse amplitudes have the values shown. No second deceleration would occur where the velocity change in the primary deceleration is 180 feet per second.

Eiband's summary of the literature pertaining to human tolerance to impact is perhaps the best known of the reports generated by the NACA program (Eiband, 1959). Eiband attempted to consolidate all of the data pertaining to impact tolerance limits published at that time. He considered data from both animal and human tests, and compared and presented the data on the basis of a trapezoidal shaped impact pulse for impact accelerations directed towards the spine, sternum, head and "tail." Note 6

Results of Eiband's survey indicated that adequate torso and extremity restraint was the primary variable in establishing tolerance limits. Only when adequate restraint was provided did the variables of impact direction, magnitude and rate of onset govern maximum tolerance and injury levels. Survival of impact forces increased with increased distribution of force to the entire skeleton, for all impacts from all directions. He suggested that the major portion of the impact force should be transmitted directly to the pelvic structure and not via the vertebral column. Accordingly, the restraints should be designed to support the vertebral column and pelvic girdle as nearly as possible in the normal standing alignment. Restraining straps that apply forces to soft abdominal tissue should be avoided.

Following this guidance, Eiband suggested that the aft-facing seats would offer maximum body support with minimum objectionable harnessing, but cautioned that such a seat, "whether designed for 20, 30 or 40 G dynamic loading," should include lap strap, chest strap, a winged back (to increase headward and lateral G protection), full-height integral head rest, load bearing arm rests with recessed hand holds and provisions to prevent the arms from slipping either laterally or beyond the seat back, and leg support to keep the legs from being wedged under the seat. For forward facing seats, he suggested that proper restraint would require lap, shoulder and thigh straps, lap belt tie-down strap, and a full height seat back with integral head support.

Eiband's summary plot for headward acceleration is shown in Figure 10. This plot is typical of the presentation of data in the report. It will be noted that the plot combines data from tests of human subjects (to define the area of voluntary exposure) with data from animal tests (to define the area of serious injury). No corrections for size or species differences were attempted. Also, in this figure, the area representing "Limits upon which current ejection seats are designed" is taken from a translation of the 1944 study by Geertz (op. cit.) which described the area as limits of static and dynamic tolerance of vertebra. Note 7

As this first NACA/NASA program was being completed, Pinkel used the data to compare the potential performance of forward and rearward facing passenger seats for transport airplanes (Pinkel, 1959). He considered seat weight, seat strength and the ability to protect the passenger from injury as factors in his analysis. From the data taken during the transport crashes, he suggested that a design crash pulse should have a primary pulse with a duration between 0.08 and 0.7 seconds, a secondary pulse with a duration of about 0.04 seconds, with the secondary pulse representing 40 percent of the total magnitude of airplane deceleration. The seats should provide energy absorption through plastic deformation which was four times the energy needed to bring the seat to its elastic limit. Passenger restraint forces were applied through the seat-belt attachment points on the forward facing seat and through the seat back, at a point twice the distance of the seat-belt attachment points to the floor, on the rear facing seat. He then considered forward facing seats having design strengths (at the yield point) of 10, 20 and 30 G. Because of the difference in height of the load application point, rearward facing seats of the same weight as these forward facing seats would have half of the design strength, e.g. 5, 10, and 15 G, if the increase in weight due to the need for a stronger seat back was ignored. Then, assuming a non-structural weight of 8 pounds per seat, he estimated that the total weight of these seats would be 32, 41 and 49 pounds, respectively, when designed for carrying a 200 pound passenger.

The dynamic analysis indicated that, for equal seat weights, the difference in strength between forward and rear facing seats would be less for short duration deceleration pulses than for longer duration pulses. For crash pulses having durations greater than 0.125 seconds, the analysis indicated that forward facing seats would have significantly greater strength than rear facing seats of the same weight. To accommodate these conditions. he suggested that dynamic tests for evaluating seat performance should provide test impact durations covering the range of 0.083 to 0.5 seconds.

Pinkel then attempted to outline a procedure for defining the relative benefits of forward facing and rearward facing airplane seats, but recognized that the lack of data on aircraft crash environments and on passenger injury tolerance would preclude a rigorous assessment. However, his discussion identified two conflicting considerations:

- In crashes involving fire or ditching, it is important that the passengers survive the actual crash with only minor injuries, so that they can evacuate the airplane. Rearward facing seats were expected to provide better protection from injury, and appeared to have an advantage under these conditions.

- In crashes which do not involve fire or ditching, rapid and unassisted evacuation of the airplane is not so critical, and a higher level of injury might be acceptable. The forward facing seat was expected to have greater strength than a rear facing seat of equivalent weight, and thus restrain the passenger in more severe crashes. Since a passenger who is held in place by his seat generally fares better than one who breaks free, a forward facing seat appeared to have an advantage under these conditions.

Thus, depending on the conditions of the crash, either forward facing or rear facing seats could have advantages. Pinkle also mentioned "complicating factors" such as restraint system slack, shoulder belts for use in forward facing seats, and loose objects in the airplane impacting passengers in rear facing seats, briefly discussed the positions a seated passenger should take in anticipation of a crash, and suggested a novel type of dynamic test facility.

Other Programs.

While the CIR/AvCIR/AvSER and NACA/NASA projects provided the bulk of data for improving survivability in aircraft crashes, several other smaller programs also made significant contributions. The U.S. Navy initiated work in several areas. Studies at the Naval Medical Research Institute compared the breaking strength of restraint systems to injuries in crashes in an attempt to define human tolerance, and developed a "reverse loading" test facility in which rapidly applied restraint forces were imposed on a stationary human subject in an attempt to relate restraint characteristics to human tolerance (Bierman, various cites, Wurzel, 1948). In 1948, a pilot seat from an F6F fighter airplane was subjected to static and dynamic tests (Gottlieb, 1948). Modifications were developed during this program which could increase the strength of the seat and restraint system to 40 G.Note 8 In a separate program, drone aircraft were instrumented to measure crash forces (Mackie, 1956a, 1956b). Vertical decelerations up to 55 G and longitudinal decelerations in excess of 48 G were measured in crashes where the cockpit remained intact.

In 1957, the U.S. Navy Air Crew Equipment Laboratory reported the design of one of the first energy absorbing seats to be placed in operation (Woodward, 1957). This system was designed for the ejection seat of the F7U-3 fighter airplane. This airplane required a high angle of attack for take-off and landing, necessitating an exceptionally long nose landing gear. During carrier landings, the abrupt arresting of forward motion by the arresting cable caused several failures of the nose landing gear. This resulted in violent impact of the airplane nose with the deck. Pilots in these airplanes often suffered fractures in the spinal column. The pilot's seat system was modified by installing an energy absorber at the lower end of the ejection seat catapult. During deck impacts, the energy absorber would stroke, and allow the seat to move downward along the ejection rails to relieve the loads on the pilot. The energy absorber consisted of a slider block which carried the lower end of the ejection seat catapult, and which was attached to the bulkhead behind the seat by a stainless steel tension strap which would stretch during impact. A new thin seat cushion, made of energy-absorbing foam, was also developed for this seat.

The inefficiency caused by the progressive force elongation characteristic of the stainless steel strap energy absorber was recognized, and efforts began to develop an improved device (Aerotherm Corp, 1957-1960). Seven different concepts were developed after analytical studies defined performance requirements. These included:

1. The stainless steel tension strap which was stretched over a moving cam in an attempt to improve efficiency,
2. A unit which pulled a thin wall tube through a die,
3. A plunger device which used hydraulic fluid to expand a stainless steel "balloon" during impact,
4. A guillotine type device which sheared rivets placed across its path,
5. A bar un-bending device which pulled on the ends of a bar of metal which had been pre-formed in a zigzag pattern
6. A unit which unwound a bar of metal which had been coiled on a reel, and
7. A "rod roll-unroll" unit which pulled a rod of metal over a series of rollers, bending and un-bending the rod while under tension from the pull.

This study was perhaps the first, of many studies to follow, to evaluate a variety of energy absorbing concepts specifically for aircraft seat use. The study also designed installations for the energy absorbers in ejection seats for fighter airplanes and in crew seats for rotary wing aircraft.

The "tube-through-die" energy absorber was developed and installed on a catapult seat and a helicopter crew seat for static and dynamic testing (Langner, 1960). The energy absorbers performed well in the tests. The unit for the ejection seat provided 4 inches of energy absorbing motion with a force of 7600 pounds, and weighed 3.31 pounds. The dual energy absorber installation for the helicopter crew seat also provided 4 inches of energy absorbing motion, but at 4810 pounds of force (due to the lighter seat weight). This installation added 5.8 pounds to the seat weight.

These tests were conducted by the Air Crew Equipment Laboratory of the Naval Air Material Center, and were part of a continuing internal program to investigate both the structure of seat and restraint systems and the human response to impact forces (e.g., Evans, 1954, Noble, 1961).

Perhaps the best known of the military programs to define human tolerance to impact were those of Stapp and his associates. The results of these studies have been extensively reported in the literature (e.g. Stapp, 1955, 1971, Beeding, 1960). Since human tolerance is not the primary focus of this summary, we need not recount the human tolerance aspects of that work other than to note that the voluntary whole body tolerance to decelerations in excess of 40 G were demonstrated for properly restrained subjects in both the forward facing and rearward facing impact positions. The development of "proper restraint" for these human tests was accomplished during the first phase of the studies (Stapp, 1949, 1951). The restraint harness for backward facing impacts ($+G_x$) was not critical since the primary impact forces were distributed over the body by the seat back. A simple lap belt of three inch wide webbing was sufficient. The various configurations of restraint systems used by Stapp in the forward facing impact tests are shown in Figure 11.[Note 9] Wrist straps and foot straps were necessary in these tests. In forward facing impacts ($-G_x$), the traditional military torso restraint, consisting of a three inch wide lap belt with dual shoulder belts, 1.75 inches wide attached to the midpoint of the lap belt, limited voluntary tolerance to about 17 G. The shoulder belts would pull the lap belt up, off the pelvis into the soft abdominal tissue, so that the upper edge of the lap belt lodged against the lower margins of the ribs. One subject suffered broken rib cartilage at about 12 G. In addition, the lower torso would move under the belt (submarine) so that the spinal column was flexed, and could not sustain high vertical impact components. To correct these deficiencies, Stapp attached two three inch wide straps to the rear corners of the intersection of the seat pan and seat back, passed them over the seat cushion (underneath the thighs) and then flaring the straps around the inside of the thighs to attach to the lap belt. Eventually, the two straps were combined into one single strap (an "inverted -V"), which was looped over the lap belt buckle so that release of the buckle would release all the straps forming the restraint. Stapp estimated that the inverted -V leg strap allowed 30 percent of the restraint load to be taken by the shoulder straps, 45 percent taken by the lap belt, and 25 percent taken by the inverted -V leg straps. Forward motion of the knees was less than 5 inches in tests which used the inverted -V strap. The inverted -V restraint system, usually with all straps made of a double thickness of three inch wide nylon or dacron webbing, became the standard configuration for most research done by Stapp and his associates.

During this period, much of the research pertaining to safety in civil aircraft emergencies was done by Swearingen and his associates working in the medical laboratories of the CAA/FAA in the United States (Holbrook, 1974). This small group was responsible for carrying out research relating to human performance, protection and survival in civil aircraft emergency situations. In the area of impact protection and survival, their work in voluntary tolerance to vertical impact (Swearingen, 1960), facial injury and protection (Swearingen, 1965, 1966a, 1966b, 1971) and accident investigation (Swearingen, 1971, 1972) are best known. The data on the centers of gravity of adults (Swearingen, 1962), children (Swearingen, 1965) and infants (Swearingen, 1969), on sitting pressures (Swearingen, 1962), and on occupant kinematics during impact (Swearingen, 1962) provided valuable information for designing protective equipment. Their early recognition of the need for dynamic testing for evaluating the performance of seat and restraint systems led to the development of one of the first anthropomorphic dummies suitable for this testing (Swearingen, 1951).

This anthropomorphic dummy was used by Beech Aircraft Corporation in conducting dynamic tests of a new restraint system with a double strap shoulder harness for the Model C35 Bonanza airplane (Beech Aircraft, 1951, and undated). This airplane, and the Model 50 Twin Bonanza, were developed in response to the findings of the CIR project under De Haven. Among the advanced features incorporated in these airplanes were a long nose section for greater crush distance, a fuselage with a reinforced keel to reduce earth plowing during impact, a reinforced crash resistant fuselage with the cabin located so that most of the aircraft mass was forward of the occupants, an instrument panel with shock mounts designed to shear during impact so that the panel would move away from the occupant, and control wheels with broad, flat impact surfaces to reduce the chance of penetrating injuries.

Other efforts were made by the civil aviation community to incorporate the recommendations of the CIR project. The provisions of shoulder belts in the Meyers 145 and the Helio Courier have already been mentioned. The 1952 CAA-Texas A&M College AG-1 prototype agricultural airplane incorporated a "40 G seat" and a restraint system designed to protect the occupant in 75 mph crashes. The pilot had excellent visibility. His seat was displaced away from the nose and all disposable loads were placed in front of the cockpit. A high head rest structure and tubular guard protected the pilot in case of an overturn accident. The "40 G" cockpit possessed independent structural integrity.

It was placed behind the engine and engine mounts (which were designed to crush at 15 G to absorb energy), the firewall (which would collapse and absorb more energy), and the hopper (which was designed to crush and absorb energy at 25 G). After several successful flights, the prototype airplane lost power in a climbing turn while on a demonstration flight. The pilot nosed the plane down, and unsuccessfully attempted to regain power. The left wing impacted a powerline pole, tearing it from the aircraft. The plane traveled 15 feet before the right wing hit a heavy fence post made of a railroad tie. This caused the nose of the aircraft to impact the ground. The plane cartwheeled, landed inverted, and slid upside down for several feet before coming to a stop. The pilot's only injury was a bruised thumb from pressing the control stick too hard.

This airplane became a prototype for several commercially produced agricultural aircraft, and the design has been proven successful in crashes (Weick, undated; Swearingen, 1972). Designers of transport seats also incorporated crashworthy features in their designs. The Aerotherm "e/a" passenger seat used extendable rear legs which provided over 6 inches of horizontal motion at 9.2 G (Thermix Corp., 1958; Aerotherm, 1958). A rearward facing passenger seat, with front legs that stroked at 16 G, was also provided to the U. S. Air Force (Aerotec, 1961). A similar concept was used in the UOP Model 723 three passenger seat assemblies, except that each seat pan was independently linked to a floor frame by two energy absorbers. Weber Aircraft developed a three passenger seat with extension type energy absorbers on the rear legs, and conducted 30 G impact tests with one, two and three occupants to demonstrate that the seat would work under asymmetric loading. Similar aft-facing energy absorbing seats were designed for the U.S. Air Force, and were tested to almost 20 G impacts (Carmody, 1962). Lap belt energy absorbers were developed for seats by Hardman and Convair. The Hardman device used a stainless steel tension rod which was stretched by a cable and pulley device attached to the lap belt. It was designed for 35 G impacts with a 0.03 s duration (Cannon, 1986). The Convair Model 22 seat belts pulled a square mandrel through a round ductile tube at loads over 9 G (Shaw, 1958; Brehaut, 1962). The Convair Model 22 seats also incorporated lightweight crushable seat backs to reduce head injury, and ductile seat front legs which would absorb energy as they collapsed and lowered the center of mass of the seat and passengers (Sifuentes, 1958; Brehaut, 1962). Teco, Inc., manufactured the "Form-Fitted Mason Seat" which absorbed energy as each form-fitted seat bucket rotated around a single cross tube under the multiple occupant seat assembly (Teco,Inc., undated). The energy absorbing device in this seat consisted of a wide hook which was pulled through a narrow slot in a ductile steel plate as the seat rotated 62 degrees.

Unfortunately, this progress received little recognition or appreciation. By the late 1960's, new transport passenger seats were being designed to reduce weight and cost, and to increase passenger density. These factors worked against the incorporation of special components just to provide improved performance in a crash. While some seats used ductile material for the legs, and others would absorb considerable energy during deformation of the basic structure, these features were mostly by-products of the design rather than a specific design goal. The Beech effort received the most discouragement. Purchasers of the airplanes often objected to the installation of shoulder belts, and would request that they be removed, or would simply cut them out. While the "invisible" crash protection features continued to be a part of the basic aircraft design, the restraint system became a rare option. The original builders of the Meyers aircraft were sold their interest in the project, and shoulder restraints were not continued. Only the builders of the Helio Courier and the agricultural aircraft were able to successfully incorporate crashworthiness as a special feature.

Notes for Chapter 2

Note 1: Although the requirements for certification of safety belts was reduced from 3000 lbs to 1500 lbs by Technical Standard Order C-22 in July, 1950, many belts continued to be manufactured in accordance with the higher industry standard, even though they were marked only in accordance with the lower certification requirement. It should also be noted that certification requirements are seldom imposed on a retroactive basis, so that aircraft certified with the 1000 lb safety belts could continue to be produced with those belts even after the effective date of the stronger requirement.

Note 2. The assistance of Mr. Kent Smith (Safety and Survivability Technical Area, Aeronautical Systems Division, Aviation Applied Technology Directorate, Fort Eustis, Virginia) in preparing this table is gratefully acknowledged.

This was a difficult table to prepare. The individual reports describing the various experiments conducted on each drop test were not always consistent in their description of the test conditions. The data given in the table represent the best estimate of the author as to the appropriate conditions for each test. Some of the tests made for fuel systems or post crash fire analysis used a previously crashed aircraft, eliminating the need for an additional aircraft. The references listed in this table were limited to those published by the sponsor of the research, and are in the public domain. A diligent search by a helpful librarian should locate copies of these reports for the interested reader. Many of these tests were also reported in a corporate AvSER report series. Unfortunately, AvSER is no longer active, so the reports are difficult to obtain. Thus, they have not been listed in the table.

Note 4: These revisions were done by Dynamic Science, a division of Marshall Industries, which had assumed responsibility for the engineering aspects of AvSER. They were the last major contribution of the CIR/AvCIR/AvSER group, as the resources available for Dynamic Science became increasingly dependent on automobile research.

Note 5: The controlled impact demonstration (CID) of a B-720 aircraft in December, 1984, did not generate a sufficient crash environment to enable the technical evaluation of crash injury protection techniques.

Note 6: Confusion regarding impact terminology has been one of the more consistent problems of human impact research. Several attempts to achieve voluntary standardization of the terminology have been made, with only partial success. Clark, Hardie and Crosbie (1961) proposed a "physiological acceleration" terminology based on the total reactive force divided by the body mass. In this system, the $+G_z$ axis was chosen "down the spine" to represent an acceleration which caused the heart, etc. to displace downward (caudally). The $+G_x$ designation was for accelerations causing the heart to be displaced back towards the spine, and $+G_y$ for accelerations causing the heart to be displaced to the left. Unfortunately, this generated a left hand axis system, and was not universally adopted. Perhaps more unfortunate, some researchers adopted the terminology, but changed the interpretation to meet their own needs. Often (but not always), this change takes the form of changing the direction of $+G_y$ to represent accelerations which would cause the heart to be displaced to the right so that a right hand axis system would result. More recently, government agencies have suggested a sign convention in which the positive z axis is downward, so that $+G_z$ acceleration would cause the heart to displace upward (cephalad) (NHTSA, 1985; FAA, 1989), with other axis remaining the same as proposed by Clark, et al. The literature is further confused by the frequent use of these axis to describe acceleration along the vehicle axis rather than the body axis, and the lack of any conventions for describing impacts which have components along two or three axis. This report will use the terminology contained in the reference which is being presented unless there is a high risk of misunderstanding.

Note 7: This same Eiband Figure was reproduced without change in the first (1967 - 1971) issues of the U.S. Army Crash Survival Design Guide (op. cit.). However, the 1971 issue of the Military Specification for Crashworthy Seat Systems (Mil-S-58095 (AV)) redefined the area of "ejection seat limits" as the "Maximum acceptable vertical pulse acceleration and duration values." Thus, the limits suggested by Geertz in the early 1940's became a performance requirement for most energy absorbing seats of the 1980's. The most difficult design requirement imposed by this requirement was the limit that seat deceleration should not exceed 23 G for 0.006 seconds duration (the point of inflection on the curve). In reviewing the work of Geertz, we find that this point was defined primarily by injuries observed in early ejection seat tests. In those tests, two engineers and a mechanic suffered slight fractures of the vertebra, but one foreman "of athletic stature" underwent two sequential tests without injury. The tests were performed without arm supports or safety harness, and short duration accelerations were not recorded but were estimated from later test data. It would appear that the precision of the 23 G/0.006 second point could be questioned.

Note 8: The "40 G" was a measure of the response of the 200 pound dummy, not a measure of the seat (airframe) deceleration. This measurement was made in longitudinal drop tests of the seat from heights of 28 to 30 inches on to elastic pads. This would indicate an initial impact velocity of about 12 f/s, with an unknown additional contribution from rebound due to the elastic pads. Measurement of restraint system forces may be a better indicator of the severity of these tests. The average lap belt loop load was approximately 3500 pounds, and the load at the end of the shoulder harness was about 1700 pounds. Recent 26 G, 42 f/s (measured at the floor) impact tests of general aviation seats occupied by a 164 pound dummy resulted in lap belt loop loads of 2800 to 3300 pounds, and shoulder belt loads in excess of 2200 pounds (Chandler, 1985a, 1985b). Considering the difference in dummy weights, it would appear that these early "40 G" seat tests were not as severe as the more recent "26 G" tests.

Note 9: The chest strap shown in these figures was used to position an accelerometer package over the sternum. It was connected to the seat only by loose tether straps, and did not function as part of the restraint unless there was catastrophic failure of the regular restraint system. Fortunately, this did not happen in the human tests. Nevertheless, this chest strap has often been misinterpreted as an essential restraint component by people who fail to read the text of Stapp's report. For this reason the chest strap has been cross hatched in the figures shown in this summary. Otherwise these figures were taken from Stapp's 1951 report. It would also appear that the illustrator used artistic license in positioning the lap belt portion of the restraint system in order to emphasize the problems with the restraints. The tie-down points appear to be at waist level in the illustrations. Photographs in the original reports indicate that this is incorrect. The lap belt tie-down points were located so that the lap belt was positioned across the pelvis just above the legs.

CHAPTER 3. APPLICATION OF CRASHWORTHINESS CONCEPTS

The development of crashworthiness technology in the 1950's and 1960's proceeded along different lines in the civil and military aviation communities. Attempts by civilian aircraft and seating system manufacturers to improve crash protection had been met with disinterest upon the part of their customers. Efforts by Beech to promote the improved crash protection offered by their Bonanza and Twin Bonanza airplanes were met with declining sales.[Note 1] Efforts by manufacturers of passenger seats were accepted for a time, but were eventually subordinated to the development of lightweight designs which provided for high density (closely spaced) passenger seating, and which were built under stringent cost constraints.

Other changes were also taking place. The management of the AvSER project found that the limited market for aircraft safety research could not compete with the well funded and growing demand for research pertaining to automobile safety, and redirected their efforts accordingly. Eventually they discontinued the AvSER project.[Note 2]

MILITARY ROTARY WING (HELICOPTER) AIRCRAFT.

In contrast to the rather dismaying outlook elsewhere, the military services and the supporting helicopter industry were ready to undertake major applications of crashworthiness design. By the early 1970's, developments in helicopter power trains, rotor blades and fuselage construction promised greatly increased flight performance for a new generation of U.S. Army helicopters. The publication of the 1971 edition of the U.S. Army "Crash Survival Design Guide," and the 1971 "General Specification for Crash Resistant, Non-Ejection Aircrew Seat Systems: Mil-S-58095(AV)", provided design guidance and a specification which could be used to provide improved crashworthiness in newly designed helicopters. These advances were recognized by the U.S. Army in 1972 when it issued specifications for procuring two new helicopter systems; the Utility Tactical Transport Aircraft System (UTTAS) helicopter and the Advanced Attack Helicopter (AAH). The design competitions for these procurements resulted in the first helicopters which were designed, from the onset, to provide improved occupant survival in crashes. The key design requirements for these helicopters are shown in Table 5.

<u>The Sikorsky UH-60A Blackhawk Helicopter.</u> Sikorsky Aircraft was the successful bidder for the UTTAS helicopter system. The crashworthy features of the Sikorsky UH-60A Black Hawk helicopter were described by Carnell (1975, 1978). This aircraft is a twin-engined single main rotor and canted tail rotor helicopter designed to carry a crew of three and eleven troops. Its major crashworthy design features included:

a. A cabin superstructure intended to retain the overhead engines and transmission at high load factors,
b. An energy absorbing landing gear,
c. Self sealing crashworthy fuel tanks and lines,
d. A fire extinguishing system which is automatically activated in a crash by an inertia switch,
e. Additional emergency exits on both sides of the aircraft,
f. A tail wheel designed to protect the tail rotor in high flare landings, and
g. Crashworthy, load limiting crew and troop seats.

The hazards in the crash environment which influenced the design, and the attempted design solutions, are listed in Table 6 (this table is based on data taken from Carnell, 1975).

The energy absorbing seat system initially considered for the UH-60 was based on a prototype armored pilot/copilot seat system developed as a demonstration project for MIL-S-58095(AV) (Desjardins, 1972). After considering several different seat and energy absorber configurations, a concept consisting of a armored seat bucket, a support structure which was attached to the floor and provided guide rails (tubes) for the seat bucket, and a single energy absorber was chosen for the prototype design. The seat bucket was attached to the frame by the energy absorbing mechanism, and its movement was controlled by four roller bearing assemblies which moved along the two parallel guide tubes which tilted back about 14 degrees from the vertical. Forward overturning moments were resisted by a rear supporting structure which converged to a single tie-down point at the floor. Spherical rod ends were on the three floor attachment points to allow angular misalignment without imposing bending on the seat structure. The primary energy absorbing system was an annealed stainless steel tensile tube which was backed up by two small steel cables which provided load limit changes for adjustment to a particular occupant weight. The testing and analysis accomplished under this program led to the August 27, 1971 revision of the general specification for crashworthy fixed seat systems (Mil-S-58095).

The requirements of the UH-60 helicopter included a new seat design. This seat was developed by SIMULA, Inc., under subcontract to Norton Company, prime contractor to Sikorsky. It is often called the "Norton/Simula" seat. (Figure 12) Development of this seat began in 1975, and production seats were delivered to Sikorsky in 1978 (Desjardins, et al., 1979). Each seat assembly consisted of an armored seat bucket, a seat frame, seat bottom, back, lumbar and headrest cushions, and a 5-point restraint system. The seat frame provided two guide tubes which served as rails for the low friction bearings attached to the seat bucket. The seat bucket could move down these rails at a rate limited by two energy absorbers attached between the seat bucket and the frame.

Table 5. Key Design Requirements for Crash Worthy Helicopters UH-60A and AH-64

KEY DESIGN REQUIREMENT	UH-60A	AH-64
General	TR 71-22	TR 71-22
Main Rotor Blade Strike	8 inch diameter object at outer 32 percent span without hazardous rotor or transmission displacement	2 inch diameter object without catastrophic damage 8 inch diameter object at outer 10% span without hazardous rotor or transmission displacement
Horizontal Impact	20 f/s into barrier with livable cockpit volume 40 f/s into barrier with 85% cabin length 60 f/s and 15° nose down with 95% cabin or cockpit volume	20 f/s into barrier with livable cockpit volume 60 f/s and 15° nose down with 95% volume of cockpit
Vertical Impact	38 f/s with 85% cabin volume	42 f/s with 85% cockpit volume
Lateral Impact	30 f/s with 80% cabin volume	30 f/s with 85% cockpit volume
Rollover	4 G longitudinal, 4 G vertical, 2 G lateral	4 G longitudinal, 4 G vertical, 2 G lateral
Hazardous Mass Item Retention	20 G longitudinal, 20 G vertical and 18 G lateral	20 G longitudinal, 20 G vertical, & 20 G lateral Engine 15G/15G/15G
Landing Gear	15 f/s with gear damage only 30 f/s and 10° pitch and roll with gear & airframe damage	24 f/s and 15° pitch, 12° roll with gear and blade damage only
Crew Seats	High strength per MIL-S-58095 with 12 inch stroke, except occupant deceleration limit relaxed	High Strength per MIL-S-58095 except 7.3 inch stroke
Troop Seats	11 inch vertical stroke, 18 G longitudinal and 24 G lateral strength	Not applicable
Fuel Tanks	Crashworthy per MIL-T-27422 with frangible attachments in accordance with TR 71-8 and TR 71-22	Crashworthy per MIL-T-27422 with frangible attachments in accordance with TR 71-8 and TR 71-22
Fuel Lines	Self-sealing tear resistant with self-sealing breakaway valves and couplings	Self-sealing tear resistant with self-sealing breakaway valves and couplings
Fuel Feed	Suction	Suction
Hydraulics	Fire resistant MIL-H-83282 fluid	Fire resistant MIL-H-83282 fluid
Emergency Egress	Within 5 s through doors, within 30 s through jettisonable windows with aircraft on its side	Ballistic jettison of canopy panels on either side

Notes: TR 71-22: U.S. Army Crash Survival Design Guide, 1971 Revision (AvSER, 1971)
MIL-S-58095: Military Specification, SEAT SYSTEM, CRASHWORTHY, NON-EJECTION, AIRCREW (Army, 1971)
MIL-T-27422: Military Specification, TANK, FUEL, CRASH RESISTANT, AIRCRAFT
MIL-H-83282: Military Specification, HYDRAULIC FLUID, FIRE RESISTANT SYNTHETIC HYDROCARBON BASE, AIRCRAFT
TR-71-8: Johnson, N. B., Crashworthy Fuel System Design Criteria and Analysis, USAAVLABS TR 71-8, (AD723988)

Table 6: Crashworthy Problems and Design Solutions

PHASE 1: INITIAL IMPACT - GROUND CONTACT WITH HIGH SINK SPEEDS	
PROBLEM:	Landing gear collapses
DESIGN:	Wheel gear has high energy absorption
PROBLEM:	Underfloor fuel tanks crush
DESIGN:	No underfloor fuel tanks
PROBLEM:	Landing gear driven into fuel tanks
DESIGN:	Landing gear located away from fuel tanks
PROBLEM:	Fuselage and fuel tanks penetrated by rocks, tree stumps, etc.
DESIGN:	Fuel tanks and lines not located in the bottom of the fuselage
PROBLEM:	Broken antenna and lead wires cause sparks
DESIGN:	Flush antennas on bottom of aircraft minimize damage, locate other antennas away from fuel
PROBLEM:	Lights under fuselage crush, exposed filaments and broken wires cause sparks
DESIGN:	Lights designed to displace into structure, extra wire length reduces breakage
PHASE 2: LOADS BUILD UP AFTER INITIAL IMPACT	
PROBLEM:	Longitudinal loads increase as fuselage digs into ground
DESIGN:	Smooth rounded underside and longitudinal keel beams resist plowing action
PROBLEM:	Sliding doors and windows jam
DESIGN:	Sidewalls designed to resist "parallelogramming" under 20 G forward and 10 G vertical loads
PROBLEM:	Feet are trapped under foot pedals
DESIGN:	Pedals are shielded to resist foot entrapment
PROBLEM:	Tailcone breaks, wires are pulled out and broken
DESIGN:	Tailcone break point is well aft of the fuel tanks, extra wire length minimizes damage
PROBLEM:	Fuel tank fittings pull out, fuel spills
DESIGN:	Tanks equipped with fail-safe break away fittings
PROBLEM:	Fuel cells snag on structure, fuel spills
DESIGN:	Simple, almost rectangular fuel cells cannot snag or tear
PROBLEM:	Fuel quantity probe pierces fuel tank
DESIGN:	Probe has low flexural strength and a rounded shoe at the end
PROBLEM:	Tanks cut and pierced by structure
DESIGN:	Structure designed to crush without penetrating the tank
PROBLEM:	Fuel lines cut and torn, fittings pulled and broken fuel spills
DESIGN:	Flexible self sealing lines, self sealing breakaway fittings, route lines away from damage
PHASE 3: MAXIMUM LOADS ATTAINED AND STRUCTURAL FAILURES OCCUR	
PROBLEM:	Engine mounts fail, engine starts to break up, flames come from inlet and exhaust
DESIGN:	Design to retain heavy components at 20 G forward and downward, 18 G sideward loads
PROBLEM:	Main gear box attachments fail, rotor blades slice into cockpit
DESIGN:	Structure designed to retain heavy components at high loads
PROBLEM:	Main gear box breaks through cabin, occupants crushed and trapped
DESIGN:	Cabin super structure to retain main gear box and prevent penetration
PROBLEM:	Sump crushed, oil lines pulled and broken, hot oil spilled
DESIGN:	Sump protected by structure, and self sealing automatic shut off when pressure is lost
PROBLEM:	Heavy cabin equipment breaks loose
DESIGN:	All interior equipment retained to 25 G loads

Table 6: Crashworthy Problems and Design Solutions, continued.

PHASE 4: MAXIMUM OCCUPANT LOADS
PROBLEM: Soft seat cushions cause spinal injury **DESIGN:** Cockpit seats stroke 12 inches at 14.5 G, cushions minimize overshoot and prevent bottoming
PROBLEM: Troop seats collapse **DESIGN:** Ceiling to floor mounted seats limit loads by stroking 10 inches at 14.5 G
PROBLEM: Shoulder harness pulls seat belt, occupant submarines **DESIGN:** Crew seats use tie down strap to position lap belt, troop seats use diagonal shoulder belt
PROBLEM: Restraint webbing folds and creases **DESIGN:** Thick webbing resists folding and creasing
PROBLEM: Occupants thrown forward, causing head injury **DESIGN:** All seats equipped with shoulder harnesses and interior of aircraft is delethalized
PROBLEM: High loads and floor deformations cause seats to break loose **DESIGN:** Seat attachment accommodates simultaneous high loading and floor deformation
PHASE 5: HELICOPTER ROLLS ON SIDE, FUEL DRAINS AND MIST
PROBLEM: Friction sparks occur when fuselage slides **DESIGN:** Aluminum underside and wheel prevent sparks
PROBLEM: Engine nacelle firewalls displace so hot metal parts of the engine are exposed **DESIGN:** Ductile firewalls maintain protection and inertial crash switch activates fire extinguishing
PROBLEM: Survival equipment displaced, damaged or lost **DESIGN:** All equipment retained under 25 G loading
PROBLEM: Engines ingest spilled fuel so exhaust flames increase **DESIGN:** Crashworthy fuel system prevents fuel spill
PROBLEM: Tank mounted fuel pumps continue to pump fuel through broken lines **DESIGN:** Pumps are suction type, mounted on the engine and driven by the engine
PROBLEM: Residual fuel drains from tanks through vent lines **DESIGN:** Vent line shut off valves prevent fuel flow
PROBLEM: Fuel ignites, causing thick smoke and toxic fumes **DESIGN:** Prevent post crash fire
PHASE 6: OCCUPANTS ESCAPE FROM HELICOPTER
PROBLEM: Multi-motion restraint release delays escape **DESIGN:** All restraints provided with single point, single motion release mechanism
PROBLEM: Sliding door jammed **DESIGN:** Provide extra emergency exits on both sides, fuselage resists "parallelogramming"
PROBLEM: Inadequate identification of exits and exit releases **DESIGN:** All emergency exits and opening instructions clearly marked
PROBLEM: Troop seat rails block emergency exits, deformation makes them difficult to remove **DESIGN:** No troop seat rails across emergency exits
PROBLEM: Lack of emergency exit releases on outside of aircraft delays rescue assistance **DESIGN:** Provide outside emergency exit releases
PROBLEM: Difficulty in escaping from aircraft on its side because of wide cabin **DESIGN:** Seats can be used as ladder
PROBLEM: Exit release handles snag clothing **DESIGN:** Release handles leave opening clear after actuation

This seat, the first to undergo all the tests required by the new military standards, was designed in accordance with general specifications provided by Sikorsky. The primary considerations in the design of this seat were to provide the occupant with protection from ballistic fire during helicopter operation and from crash injury during accidents, while retaining comfort for prolonged flights. The armored seat bucket provided 5.8 square feet of ballistic protection and structural support for the bottom, back, sides and thighs of the occupant. It was constructed of a 13 ply laminate of Kevlar 49 faced with boron carbide ceramic tile in those areas requiring ballistic protection. A nylon spall shield covered the tile and all cut edges of the Kevlar. The tile was cut away at attachment points so that frame bracket and restraint system loads were applied directly to the Kevlar shell, thus avoiding loads which might crack the brittle ceramic tile. The seat cushion was designed to fit occupants between 2nd and 98th percentile size, and attempts to maximize load distribution over the greatest buttocks area. The cushion is made of foamed polyethylene, lined with a thin intermediate layer of loading-rate-sensitive polyurethane foam and a top layer of reticulated polyurethane foam. The entire cushion is covered by a fire resistant, open-weave nylon material. The construction of this cushion was intended to provide a relatively rigid and comfortable link between the occupant and the seat bucket. In an attempt to minimize the relative motion of the occupant and the seat during a crash, the cushion was designed to compress under the weight of the occupant to within one-half inch of the bucket. The five-point restraint system was made of low elongation webbing (not more than 7.5 percent elongation at design loads) and used a single rotary release buckle at the intersection of the dual shoulder belts, both lap belt straps, and the lap belt tie-down strap (Negative-G strap). The dual shoulder belts were attached, with a single strap, to an inertia reel attached to the back of the seat bucket.

The seat frame provided two vertical guide tubes with three crossmembers, two longitudinal struts between the front and rear track fittings, and two diagonal struts fitted between the middle guide tube crossmember and the front track fittings. The guide tubes served as races for the low friction seat bucket bearings, permitting easy vertical movement of the seat bucket relative to the frame. Two energy absorbers, attached between the upper guide tube crossmember and the seat bucket, restrained the seat bucket. The "inversion tube" energy absorbers used in this seat were tensile devices that generate a constant force by turning a thin-walled metal tube inside out. As designed for this seat, each energy absorber generated a force of slightly over 1100 pounds for a stroking distance of approximately 16 inches, allowing the seat to stroke at a load factor of 14.5 G. The seat frame provided spherical bearings at the attachment of the diagonal struts to the front track fittings and the middle crossmember, and at the attachment of the lower crossmember and the rear track fittings. The bearings were pinned in place for normal operations. However, when the floor warped during a crash, the pins would shear to allow the seat to accommodate the floor deformation without significantly increasing the forces on the seat structure, the tracks, or the helicopter floor. Further details of this seat, and the results of the various static and dynamic tests can be found in Desjardins, et al., op. cit.

The troop seats used in the cabin of the UH-60 were modeled after seats developed by the U.S. Navy (Reilly, 1971) and which then served as prototypes for the U.S. Army Crash Survival Design Guide (Singley and Desjardins, 1978; Reilly, 1974, 1977). (Figure 13) Both forward facing and rearward facing seats developed under this effort were similar in construction. The seats were suspended from overhead aircraft structure by wire-bending energy absorbers (Boeing/Vertol, 1965) which provided energy attenuation in the vertical direction. The seat back frame was made of tubular structure in a trapezoidal shape. The seat pan frame was also made of tubular structure, and was pivoted to the back frame at the base of the trapezoid. The seat pan frame was held in a horizontal plane by webbing tension straps running from the top of the back frame to attachment fittings located on the sides of the seat pan frame, approximately one third of the length of the sides, from the pivot. A fabric seat pan membrane, and a fabric panel between the webbing straps formed the seat surface. A flap in the back panel could be removed to allow access to a pocket which would accommodate a combat back pack. Stability in the longitudinal direction was provided by energy attenuator struts which ran diagonally from the front corners of the sat pan to the floor on forward facing seats, and reversed on rearward facing seats. These struts were intended to rotate downward without stroking during vertical crash impact conditions. Lateral stability was provided by crossed cables running from the front and rear corners of the seat pan to the floor. Lap belts and dual shoulder belts were attached to the seat frame.[Note 3]

In the early 1970's, the U.S. Army and U.S. Navy began cooperation on the development of a Joint Army-Navy (JAN) crewseat (Domzalski, et al., 1978). The prototype of this seat used six "rolling torus" cyclic energy absorbers to suspend the seat bucket from a frame (ARA, 1972; Mazelsky, 1974). (Figure 14) The design provided energy absorption, by translation and rotation, in all directions. A modification of this design was developed for the Service Life Extension Program of the H-64 helicopter. The vertical stroking component of that installation is 6.5 inches, the maximum space available between the bottom of the seat and the floor in the H-64. This seat was approved for service in 1978, so that the CH-64 became the first U.S. Navy helicopter to have crashworthy crew seats installed. In 1974, the JAN project began to consider the feasibility of a standardized armored crashworthy crew seat for use in future helicopters. The aircraft which were candidates for a standardized seat, at that time, were the Boeing Vertol High Lift Helicopter, the Boeing Vertol UTTAS, the Sikorsky Aircraft UTTAS, the Bell Helicopter Textron AAH and the Hughes Aircraft AAH. The study determined that an efficient standardized seat system could not be designed for all five aircraft because of the wide variation in requirements for ballistic threat and energy absoption and the limitations created by the design of the airframes on the design of the seat carriage. It was then decided to standardize the major seat components such as the basic bucket and associated armor, the energy absorbing device, the seat cushions, and the restraint system. The previous JAN seat effort became the model for these developments. The design and fabrication study of such a seat indicated that significant weight and cost savings could result from a standardized component concept (Mazelsky, 1975).

Various factors caused all the candidate aircraft except the UH-60 to be dropped from consideration for the JAN project. The objective became the development of a candidate seating system for future deliveries of the UH-60 helicopter. The final design developed by Aerospace Research Associates, Inc. (ARA) used a Kevlar covered armor steel seat bucket which was suspended from the seat frame by six Tor-Shok energy absorbers which attenuated vertical, longitudinal and lateral crash loads. This seat is installed in late production UH-60A helicopters.[Note 4]

Seats which provide uniaxial energy absroption in the vertical direction, such as the Norton/Simula seat, are usually considered adequate for protecting the occupant from spinal column injury in a crash. Since a well restrained occupant is more tolerant of impact acceleration in the horizontal directions (lateral, forward, rearward), significant energy absorption is not usually provided in that plane. Nevertheless, forces acting on the body in the horizontal directions could be reduced if energy absorption is provided in those directions. This potential reduction in forces is obtained at the expense of increased motion of the occupant within the cockpit, with a resultant increase in risk of secondary impact between the occupant and the cockpit interior furnishings. The U.S. Army sponsored tests at the FAA Civil Aeromedical Institute to compare the performance of the uniaxial (Norton/Simula) and multiaxial (ARA) seat designs used in the UH-60 (Melvin, 1985; Vyrnwy-Jones, in press). Tests were made with the uniaxial energy absorbing seat and the multiaxial energy absorbing seat under nearly identical conditions. The results are summarized in Table 7. It can be seen that the displacement of the dummys head, relative to the cockpit, is significantly greater with the multiaxial energy absorbing seat design. However, the maximum velocity of the head, relative to the interior of the cockpit, was not significantly different between the two designs. The vertical seat stroke of the multiaxial energy absorbing seat was less than that of the uniaxial energy absorbing seat in all tests having a vertical impact component. This may result from the complex motion of the multiaxial seat under impact condition, compared to the relatively constrained movement of the uniaxial seat. The studies concluded that:

a. The uniaxial seat design gave consistently lower lumbar spinal column loads than did the multiaxial seat,
b. The forward and lateral displacement of the multiaxial seat design increased the flail envelope of the dummies by as much as 60 percent,
c. The complex motion of the multiaxial seat could prevent the multiaxial seat from stroking through the opening provided in the cockpit floor of the UH-60, and
d. The multiaxial seat did not significantly reduce the head or chest accelerations measured in the dummy in horizontal tests.

The Army specification for crash-resistant aircrew seats was amended in 1986 to require the use of vertical energy absorbers (Army, 1986).

<u>The Hughes YAH-64 Advanced Attack Helicopter</u>. The crashworthy seat on the Hughes YAH-64 helicopter followed the basic design of the Norton/Simula seat for the UH-60A, except for changes in armor placement and adaptation to bulkhead mounting. The adaptation to mount the seat on the bulkhead of the cockpit was done by modifying the guide tubes so that they attached directly to fittings on the structural bulkhead, thus eliminating the seat support frame which is required for floor mounted seats. The effect of landing gear energy absorption was considered in the design and testing of the seat, so that the energy absorbing stroke of the seat could be reduced. Additional information on crew protection in the YAH-64 helicopter is given in the report by McDermott (1978).

<u>Variable Load Energy Absorbers</u>. Many different designs of energy absorbing mechanisms have been developed for use in aircraft seats and for other shock-load applications. The basic function of an energy absorbing mechanism or structure is simply to limit the forces transmitted through the mechanism by allowing the mechanism or structure to undergo permanent deformation. For practical application in seats, the energy absorber must also be efficient, that is have a relatively high energy dissipation per unit weight, and must limit the force transmitted through the mechanism so that it protects the seat occupant from injury and/or reduces structural forces in the seat or airframe to acceptable levels. The energy absorber must also achieve these goals within the tight space of the cabin or cockpit. An efficient energy absorber must therefore limit the transmitted force at the highest levels consistent with the desired protection of the occupant or the structure. This has caused several problems in the design of energy absorbing seating systems.

The goal of protecting the occupant from excessive vertical or spinal loading was specified by limiting seat acceleration in the vertical direction to the area of acceptable acceleration magnitude-duration specified by the Eiband tolerance curve (e.g., Army, 1971). In effect, this criteria limited the duration of seat acceleration in excess of 23 G to not more than 0.025 seconds. This acceleration measurement was to be

Table 7. Comparison of Seat Performance in Dynamic Tests

Test Conditions								Results	
Vel, m/s or (f/s)	Max. peak G	Direction of major Impact	Seat orientation in degrees: yaw	pitch	roll	Occupant weight in pounds	Seat Type Multi or Uni Axial	Seat stroke in inches	Horizontal head displacement in inches
16.5 (54)	46	Vertical	0	20	20	223	Uni	9.0	19
16.5 (54)	46	Vertical	0	20	20	223	Multi	2.3	30
13 1 (43)	44	Vertical	0	14	0	133	Uni	8.6	14
13.1 (43)	44	Vertical	)	14	0	133	Multi	5.7	28
8.5 (28)	18	Lateral	90	0	0	255	Uni	0	27
8.5 (28)	17	Lateral	90	0	0	255	Multi	0	36
17.1 (56)	29	Lateral	30	0	0	255	Uni	8.6	14
16.8 (55)	31	Lateral	30	0	0	255	Multi	2.2[1] 6.0[2]	45

Notes: 1. Forward displacement
2. Vertical displacement

made on the bottom of the seat bucket. However, since the seat/occupant system is a dynamic system, a simple constant-force energy absorber caused excessive seat accelerations to be measured on the seat bucket at times when the elastic response of the seat/occupant system was not loading the seat (e.g., Desjardins, 1978). These excessive seat accelerations occurred out of phase with the occupants spinal column loading, i.e., the high seat accelerations occurred at times of low spinal column compression. Attempts to model the dynamic response of the seat/occupant system as a simple damped mass-spring system (using the DRI model) resulted in the conclusion that an energy absorber which transmitted a high initial force, followed by a low force, followed by a intermediate force (a "notched energy absorber") would provide optimum protection from spinal injury (Carr, 1970; Phillips, 1972). Based on the recommendations of these studies, a series of tests comparing the performance prototype notched energy absorbers with constant force energy absorbers was conducted by the U.S. Navy Air Development Center. The data from these tests indicated that the difference in performance was not statistically significant, and the project was discontinued.

The problem of designing energy absorbing seats for different seat occupant weights has been long recognized. Fixed energy absorber limit loads were typically set for the 50th percentile occupant under the conditions of a 95th percentile crash. A heavier weight occupant in the same seat and in the same crash would cause the energy absorber to stroke through a longer distance. Perhaps the energy absorber would bottom out and transmit injurious loads to the occupant. Conversely, a lighter weight occupant would not cause the energy absorber to stroke through the full distance available, and would be subject to higher acceleration and a greater risk of injury. A seat energy absorber which could adjust the force level at which it stroked could make optimum use of the available stroke distance for occupants of all weights. The prototype seat for developing the military specification for crash resistant crew seats, previously described, used a primary energy absorbing system of an annealed stainless steel tension tube which could be supplemented by two stainless steel tension cables for heavier occupants. Although that system was not placed into production, it forecast the need for additional developments.

In 1977, the British Royal Air Force purchased Boeing-Vertol Chinook helicopters with a requirement for attenuating vertical impacts of 48 G with a velocity change of 42 f/s (Campbell, 1981). With a seat attenuation level of 14.5 G for the 50th percentile occupant, calculations indicated that the 95th percentile occupant wearing a tic gear and body armor would require a seat stroke of over 16 inches. Since, with the seat at its lowest adjustment position only 7 inches of stroke distance was available, it was necessary to incorporate a variable load energy absorber. The design used three wire-bending type energy absorbers, each of which bent two wires over three rollers. The primary energy absorber provides the base level stroking force of 4100 pounds, and engaging the other two energy absorbers adds 600 pounds each. The system permits the seat occupant to select one of these three discrete load limit values, with the occupant weight ranges corresponding with three effective stroking forces. A wire bending variable load energy absorber is shown in Figure 15.

Three concepts, a wire bending mechanism, a tube constricting mechanism and a hydraulic energy absorber were studied, and the tube constricting mechanism was installed on a SH-60B crew seat for dynamic testing (Svoboda, 1981). The inversion tube energy absorbers on that seat were modified to include a ball-type tube constrictor which would act on the inversion tube as it was pulled from its housing. Six steel balls around the circumference of the tube could be moved radially inward by a push-pull control handle to increase the stroke force. (Figure 16) The limit load on the inversion tube was set for the weight of a fifth percentile occupant, and the penetration of the balls into the tube as it extended could adjust the limit force for occupants up to the 95th percentile weight. Dynamic tests were conducted with anthropomorphic dummy seat occupant weights representing 5th percentile through 95th percentile fully equipped male pilots. The seat stroked 9.5 inches with the low occupant weight, and 11.1 to 11.6 inches with the high occupant weight, a decided improvement when compared to the non-adjustable SH-60B system (Domzalski, 1982; 1983).

The potential for error or neglect in setting the manually controlled variable energy absorber led to the development of automatically controlled variable energy absorbers (Warrick, 1984). An acceleration sensitive relief valve controlled the fluid flow in a hydraulic shock absorber to limit seat acceleration during impact to 14.5 G. (Figure 17) The hydraulic shock absorber operated in parallel to a fixed load energy absorber which was sized to provide the force necessary to limit the seat acceleration to 14.5 G when the seat was occupied by a 5th percentile male occupant. The flow controlled Hydraulic shock absorber would then provide the additional force to control the motion of the seat when occupied by heavier occupants. Dynamic tests to evaluate this system were conducted using a light weight seat bucket and anthropomorphic dummies weighing from 164 to 218 pounds (Glatz, 1988). These tests indicated that the automatically controlled variable energy absorber performance was comparable to that of manually adjusted variable energy absorbers, and was less affected by variation in the onset rate of the impact pulse.

Inflatable Concepts for Crash Worthy Seats and Restraints. Inflatable seating and/or restraint has been suggested as a means of obtaining improved crash protection for many years. This summary will concentrate on aircraft applications, and only note in passing that airbag restraint systems for automobiles are just now coming on the marketplace after years of deliberation. Armstrong's suggestion in 1939 for inflated rubber passenger seat backs for providing upper body support for a passenger seated behind the seat has already been noted. Clark (1966) reviewed early applications of air bags in aircraft crashes. It was rumored that some aircrew members serving in World War II would inflate their life vests to obtain protection just before a crash. The Royal Aircraft Establishment investigated the "Pekarek Safety Cell" concept of inflatable devices for restraint systems during the early 1940's (Petrecek, 1942, 1943a, 1943b). A sketch dated March, 1952 shows a manually triggered airbag system placed in the back of airplane passenger seats. In 1959, Douglas Aircraft suggested a "freedom-restraint" provided by bags inflated around a lap shelf in the cockpit. The Martin Company completed an extensive development program of airbag seat (the "Airseat") and restraint systems (the "Airstop") in the 1960's (Clark, 1964a, 1964b, 1964c, 1965, 1966a, 1966b; Cooper, 1963). This work led to the inclusion of the Airstop restraints in passenger seats in the previously described 1964 DC-7 crash test by AvSER (Clark, 1966a) and of the Airseat in an AvSER crash of a C-45 airplane in 1965 (Clark, 1966b). Snyder conducted crash injury tests with airbags (1966), and discussed applications to transport aircraft (1974, 1976, 1977). A study supported by the U.S. Navy investigated the use of an inflatable collar to protect the head against violent rotation during a crash (Ezra, 1972). The FAA included inflatable restraint systems in a study of general aviation occupant restraint systems (Sommers, 1973). The U.S. Air Force studied airbags as a supplementary lateral restraint in the F-111 escape capsule (Shaffer, 1974). A 1975 study considered the possibility of using an air bag to protect the gunner from injury caused by impacting the rigid column sighting device (Loushine, 1975). Underseat energy absorbers in the form of a bellows or a bell shaped air bag have been considered for seats in small airplanes (Warrick, 1979).

The concept of an inflatable seat was developed further by Fire Proof Tanks, Ltd. a subsidiary of Westland Helicopters, Ltd. (Thompson, 1979; Reader, 1979). This three passenger seat offered increased comfort, the absence of rigid and possibly injury causing rigid structural members, ease of installation for quick change of aircraft mission, minimal weight and bulk when deflated, and the possibility for use as a personal emergency flotation device in case of aircraft ditching. The seat consists of separate base and back rest airbags, joined along the upper rear edge of the base. The shape of bags is maintained by internal diaphragms. A lap belt and single diagonal torso belt restraint system is provided for each passenger. The restraint system is anchored to airframe structure, and the airbag is tied to the aircraft floor by nylon ropes through tags on each side of the seat. The system successfully completed longitudinal, la .al and vertical 26 f/s (8 m/s) impact tests at 10G while restraining three 95th percentile dummies. A 26 f/s (8 m/s) vertical impact test at 22.8 G with two 95th percentile dummies and one 50th percentile dummy was also successful. A vertical impact test with bag pressure equivalent to a 28 G test did not damage the bags.

The U.S. Naval Air Development Center developed the concept of the "Inflatable Body And Head Restraint System" (IBAHRS) for improving the performance of the traditional "5-point" restraint system (dual shoulder belts, lap belt, and lap belt tie down strap)

(Schulman, 1977). The IBAHRS incorporates rapidly inflatable bladders into the shoulder belts. A crash sensor provides early detection of the crash event and initiates the firing of a gas generator which inflates the bladders. The inflated bladders remove slack in the belts and preload the restraint system. This action pulls the occupant into proper position for the forthcoming impact, removes slack from the belts, and preloads the restraint system so that it can better serve to tie the occupant to the seat. Since the bladders expand around the shoulder belts, they provide a greater and more uniform area for load distribution to reduce the severity of injury. The bladders, with proper geometry, can also support the head as it flails to reduce the likelihood of secondary head impact with the cockpit interior furnishings. The early prototype design of the IBAHRS used a bladder system that spanned the space between both shoulder belts, and thus connected the belts (Figure 18). Dynamic sled tests with anthropomorphic dummies showed that the IBAHRS could significantly reduce the restraint system forces resulting from an impact, even under conditions with slack in the belts.

The system was further developed, and used in a program of comparative tests of seven restraint systems conducted by the U.S. Army Applied Technology Laboratory with the FAA Civil Aeromedical Institute (Singley, 1981). The restraint systems used in this study were:

Type 1. A "Mil-S-58095" restraint system. This system is a 5-point restraint with both shoulder belts attached to a single inertia reel. (Figure 19)

Type 2: Similar to Type 1, but with the shoulder belts attached to a powered haul back reel instead of an inertia reel.

Type 3: A prototype 5-point restraint with reflected shoulder straps similar to the system developed by the RAF Institute of Aviation Medicine for the F-111 (Reader, 1968). The reflected shoulder straps were provided with inertia reels. (Figure 20)

Type 4: Similar to Type 3, but with a dual strap powered haul back reel instead of the inertia reels.

Type 5: An experimental IBAHRS with individual bladders under each shoulder belt. This system used a 3 inch wide lap belt with a military lift lever latch assembly. (Figure 21)

Type 6: Similar to Type 5, except using a Type 3 restraint for holding the bladders.

Type 7: Similar to Type 1 but using a RAF-GQ Ltd. rotary buckle.

Thirty three impact sled tests were performed in this program. Impact velocities ranged from 28 to 50 f/s, and decelerations ranged from 5.4 to 30 G. The tests were conducted with the seat forward facing ($-G_x$) and yawed 30 degrees with respect to the forward facing position. The anthropomorphic dummy weight, including equipment, was 227 pounds for most tests. The IBAHRS showed less upper torso, head and neck motion when compared to the other systems, although the Type 4 restraint was almost as good. There was not a significant reduction in restraint system loads when the IBAHRS was used, perhaps because of the snug fit of the other restraint systems. The rotary release buckle used on the Type 1 restraint failed in a 30 G test with 30° yaw seat position. This was attributed to point loading resulting from forced misalignment between the square cut-out in the latch plate and the square latch dog in the buckle. The problem was corrected by incorporating circular cut-out patterns in the lap belt latch plates and circular latch dogs in the lap belt buckle. Asymmetric or inconsistent deployment of the airbags in the IBAHRS was also observed in some tests. If the IBAHRS shoulder belts were tight initially, the bladders could inflate outboard of the shoulder belt rather than inboard, under the chin.

The IBAHRS has been further developed (e.g., Domzalski, 1984a; 1984b; 1984c). Thirteen failures were observed in twenty six forward facing ($-G_x$) IBAHRS impact tests conducted at impact velocities from 33 to 44 f/s with peak accelerations between 9 and 20 G. Five of the failures were due to problems with the basic host restraint system and the inertia reels. It appeared that the nominally "webbing-G sensitive" reel was also onset and rate sensitive, and would not lock reliably if the strap were withdrawn too rapidly from the reel. It was also observed that the inflating bladders could induce large bending moments in the shoulder belt latch plates, causing them to break. Six of the IBAHRS failures were due to "flip-out" or "roll-over" of one or both bladders. The two remaining IBAHRS failures were due to pressure blow-out of seams. The "flip-out" problems were associated with failures of internal ribs placed in the bladders to control the inflated shape of the bladders. The tests indicated that the IBAHRS provided increased protection as a result of reduced head displacement and potential for secondary head impact with cockpit interior furnishings, reduced head angular velocities, and reduced dynamic amplification of impact accelerations due to the improved coupling effect of the inflated bladders. It was also observed that the bladder inflation would lock the inertia reel quicker than would the normal strap loads, and thus improve restraint. Vertical IBAHRS impact tests confirmed improvements in head displacement, although that improvement was accompanied by increased head acceleration. Although the 0.15 s duration of effective pressurization of the bladders was considered adequate for the major impact in a helicopter crash, a duration of 0.3 to 0.5 s was recommended to provide for secondary impacts. A development model of the IBAHRS was installed on the Bell Helicopter Textron YAH-63 prototype for a drop test (T-41) at the NASA Langley Research Center. A malfunction of the squib circuit for the left bladder in the IBAHRS, and the failure of the right bladder gas generator to maintain adequate pressure caused the IBAHRS to fail to perform in the crash test.

Military Passenger Seat Development. The Naval Air Development Center investigated the feasibility of developing an improved passenger seat specification for fixed wing aircraft which would include dynamic testing as a means of demonstrating seat performance (Domzalski, 1980b). Data in the U.S. Army Crash Survival Design Guide and in a special study of U.S. Navy aircraft crash environment (Glancy, 1971) were consulted to define the dynamic test environment shown in Table 8. The data also indicated that most of the survivable crashes occurred within a 20 degree impact angle relative to airplane longitudinal axis. A significant requirement was that the static and dynamic tests were to be conducted under a condition simulating floor warpage simulated by twisting one (seat to floor) attachment track 10 degrees and pitching the other track 10 degrees. A design passenger weight of 225 pounds accommodated equipment carried by the passenger as well as the passenger body weight.

Table 8. Impact conditions for U.S. Navy passenger seat studies.

Impact Direction	Velocity Change, f/s	Peak Acceleration, G	Pulse Duration, s
Longitudinal	64	20	0.200
Vertical	35	36	0.060
Lateral	30	16	0.116

One aspect of this project was the design and construction of two prototype two place passenger seat systems for evaluation. The first design concept was developed by the Boeing-Vertol Company. This design was similar to that developed for the NASA Langley Research Center general aviation seat program in that a wire-bending energy absorber mechanism was connected between the floor and the seat back. Diagonal struts under the seat provided support and stability under normal flight conditions and provided guidance for the seat as it stroked under crash impact conditions. The design could be assembled as either a forward facing or rearward facing seat assembly by changing the energy absorbers (2300 pounds each for forward facing seats, 3500 pounds each for rearward facing seats) and the direction of the diagonal struts. Swivel joints were provided in the seat structure to accommodate torsional loads induced by floor warpage. The second design concept was developed by Aerospace Research Associates, Inc. The energy absorbing system consisted of six rolling torus (TOR SHOK) load limiting devices arranged as seat legs and a diagonal spreader at each end of the seat frame. Four stabilizing rods, one pair crossed between the front legs and one pair crossed between the rear legs, would undergo plastic deformation at 2500 pounds force. The seat frame and seat backs were relatively rigid box structures. Torsional loads resulting from floor distortion were accommodated by the energy absorbers and stabilizing rods, which were provided with swivel rod-end fittings at each end. Both seat concepts underwent static testing (Domzalski, op.cit.) and the ARA seat underwent dynamic testing at the FAA Civil Aeromedical Institute (Hazelsky, 1981).

Military Helicopter Accident Studies and Crash Tests. Crash data for 563 rotary wing aircraft accidents and 92 accidents of small fixed wing airplanes were reviewed in the initial attempts to define the crash environment for military helicopters. Data from only 373 of those crashes were found to be usable. These data were later supplemented by additional data from 108 attack and 10 cargo helicopters to define the crash environment (Laananen, CSDG, Vol 2, 1980). It was found that the crash environment was similar for the rotary wing aircraft and small fixed wing airplanes. It was estimated that ninety-five percent of these survivable crashes had a change in impact velocity which fell within the boundaries shown in Figure 22. Average accelerations estimated for the velocity changes along the vertical, longitudinal and lateral axes were 24 G, 15 G, and 16 to 18 G, respectively.[Note 5]

As experience was gained with those recommendations, trade-offs of crashworthiness with operational and economic factors resulted in a new set of recommendations (Army, 1988). These are summarized in Table 9.

Crash environment and injury in U.S. Army helicopters. Recent studies have provided additional data on the crash environment and injury mechanisms prevalent in newer helicopter designs (Shanahan, 1989a, 1989b). In these studies, data from 303 aircraft in 298 U.S. Army Class A and Class B mishaps involving AH-1, OH-58, UH-1 and UH-60

Table 9. Crash Impact Design Conditions with Gear Extended

Impact Direction	Impact Surface	Velocity Change, f/s
Longitudinal: Cockpit Cabin	Rigid vertical barrier	 20 40
Vertical: [1]	Rigid horizontal surface	42
Lateral: [2]		25
Lateral: [3]		30
Combined [4] Vertical: Longitudinal:	Rigid horizontal surface	 42 27
Combined [5] Vertical: Longitudinal:	Plowed soil	 14 100

Notes: 1. For the case of retracted landing gear, the seat and airframe combination shall have a vertical crash impact design velocity change capability of at least 26 f/s.
2. For light fixed wing airplanes
3. For rotary wing and tilt-prop/rotor aircraft.
4. High angle. Also see Note 1.
5. Low angle.

helicopters occurring from October, 1979 to September, 1985 were reviewed. Class A mishaps result in property or personal damages greater than $500,000 or loss of life. Class B mishaps result in property or personal damages between $100,000 and $500,000, permanent partial disability or hospitalization of five or more personnel. The aircraft data, and the number involved in the study, are shown in Table 10. Only the UH-60 included crashworthiness as a major design requirement.

Table 10. Aircraft Data

Model	Mission	Seats	Maximum Speed, knots	Gross Weight, pounds	Number in study		Mishap rate [1]	
					Class A	Class B	Class A	Class B
AH-1	Attack	2	190	10,000	37	17	5.6	2.6
OH-58	Observation	4	120	3,200	69	16	4.0	0.9
UH-1	Utility	13	124	9,500	99	35	2.2	0.8
UH-60	Utility	16	193	20,250	23	7	6.9	2.5

Note 1: Mishaps per 100,000 flying hours.

This study represented 84 percent of all U.S. Army Class A and Class B helicopter mishaps which occurred during the six year period. Sixty-three percent of the helicopters in the study impacted on a sod surface, 15 percent on a "soggy" surface, 13 percent on a prepared surface, 6.3 percent on snow, 1.6 percent in water, and 1.2 percent impacted on ice. Thus 87 percent of these crashes occurred on unprepared surfaces which could limit the effectiveness of most energy absorbing landing gear designs.

The velocity changes estimated for these crashes is shown in Table 11. The mean vertical velocity change for the UH-60 was significantly different from the others (shown by ANOVA, $p<0.001$). The higher impact velocities in the UH-60 crashes were attributed to the crashworthy features incorporated in its design. Other aircraft would sustain damage in accidents which are reported as hard landings in the UH-60. The ability of the UH-60 to withstand higher velocity impacts than other helicopters enables some high-velocity crashes to be "survivable" in the UH-60. In other helicopters, those crashes would be clearly non-survivable. However, it is also noted that the UH-60 has a higher mishap rate than other helicopters in the study, and it apparently impacts at higher vertical velocities. These factors were attributed to the operational environment of the UH-60.

its higher autorotation sink speeds, its higher disk loading, and lower rotor inertia.

Table 11. Estimated velocity change during impact.

Model	Mean Velocity Change, m/s				95th Percentile Velocity Change, m/s Survivable Only	
	All Mishaps		Survivable Only			
	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal
AH-1	6.4	11.1	4.1	6.6	12.0	17.0
OH-58	4.3	8.9	3.8	7.1	9.0	27.0
UH-1	5.2	9.2	3.5	8.1	10.2	26.2
UH-60	16.0	10.8	8.8	5.9	14.1	12.2

There were 1,060 occupants aboard the aircraft in the study. One-hundred and thirty-six (12.8%) of these occupants received fatal injuries. Three-hundred and seventy-two (35.1%) of the occupants received disabling injuries. The remaining occupants received non-disabling injuries or survived without injury. The most frequent site of fatal injuries in survivable crashes were the head (62.5%), the thorax (18.8%), and the cervical spine (12.5%). The head injuries occurred despite mandatory use of flight helmets. The distribution of injuries in survivable mishaps are shown in Table 12. Even though the crash environment of the UH-60 is more severe than the other helicopters, the rate and severity of injuries is not higher than the other designs. Again, this is attributed to the crashworthy design. The study indicated that the AH-1, OH-58, and the UH-1 mishaps produced similar distributions of injuries by body region. These were different than those produced by the UH-60 mishaps. The distribution of injuries by body region, for survivable crashes, is shown in Table 13. There is a significantly greater proportion of thoracic injury, but a significantly lower proportion of lower extremity and spinal injuries in the UH-60.

Table 12. Injury distribution in survivable mishaps, percent of total injuries in each model.

Model	Fatal	Disabling	Non-disabling	No Injury
AH-1	7.1	31.3	14.1	47.5
OH-58	6.1	43.4	10.1	40.4
UH-1	3.2	38.5	10.9	47.4
UH-60	8.1	36.1	10.5	45.4

Thermal injuries were the cause of death in only two accidents, one of which was not survivable. This absence of thermal injury is due to the success of crashworthy fuel systems which have been required on U.S. Army helicopters since the mid-1970's. Before that time, almost forty percent of the fatalities in survivable crashes were due to fire. The study concluded that:

a. The UH-60 experienced a crash rate of more than three times that of its predecessor, the UH-1.

b. The UH-60 impacted at vertical velocities considerably in excess of the design limits for the helicopter.

c. Since the degree of injury is related to the impact velocity, this factor had a major negative effect on the overall crash survivability of the UH-60.

d. The injury severity in survivable crashes was about the same for all helicopters in the study, even though the mean vertical impact velocity was considerably greater for the UH-60.

e. The effective crashworthy design of any vehicle requires that its future crash environment be accurately projected while the vehicle is in development.

Table 13. Distribution of injury by body region, in percent.

Body Region	All injury		Major/fatal injury	
	UH-60	Other	UH-60	Other
General	3.5	1.5	1.4	2.2
Head	26.9	22.3	23.0	27.4
Neck	2.9	5.1	0	2.2
Cervical spine	0.6	1.7	1.4	4.8
Thorax	25.2*	12.8*	35.1*	11.8*
Abdomen	5.3	5.2	8.1	3.8
Thoracic and lumbar vertebrae	4.7	6.8	6.8	14.5
Upper extremities	11.7	16.0	8.1	10.2
Lower extremities	19.3*	28.3*	16.2	23.1

* Significant, Chi-square, $p < 0.05$

Crash environment of U.S. Navy helicopters. A survey of the crash environment for U.S. Navy helicopters was undertaken by Simula, Inc., to define the impact environment and injury hazards (Coltman, 1986b, 1986c, 1988). All flight mishaps occurring from January, 1972 through December, 1981 were reviewed. Sixteen percent of the 184 mishaps were non-survivable. Fifty-four percent of the mishaps occurred on land, but 69 percent of the major injuries and fatalities occurred in the land impacts. The remainder of the mishaps were water impacts or ditchings. Thirty-seven significant but survivable water accidents and 64 significant but survivable land accidents were selected for detailed accident reconstruction and analysis. The impact angle and the pitch, roll and yaw angles of the helicopters at the time of impact are shown in Table 14. Thirty-six crashes occurred with a positive pitch angle, but only 24 occurred with a negative pitch angel. This was attributed to the use of a flaring maneuver often used to slow the sink rate prior to impact. The yaw angle at impact was negligible in 80 percent of the crashes, most of which had a functional tail rotor at impact. If the tail rotor was not functional, the yaw angle was uncontrolled, and ranged between 0 and 360 degrees. The distribution of vertical, longitudinal, and lateral velocity changes for the land crashes is shown in Figures 23 through 25. These data are compared with an earlier study (Glancy, 1971). The velocity changes were calculated from as the square root of the difference of the squares of the velocities at the beginning and end of the principal impact pulse.

Table 14. Aircraft Orientation at Time of Impact, percentage of aircraft at indicated angle, in degrees.

	Level	± 10°	± 20°	0-10°	10-20°	20-30°	30-45°	45-60°	60-75°	75-90°
Impact Angle	4%			11%	8%	8%	14%	6%	11%	29%
Pitch	36%	65%	84%							
Roll	54%	63%	72%							
Yaw	63%	65%	70%							

Two hundred ninety-four occupants received major or fatal injuries in these crashes. Seat and restraint systems, either through failure, misuse, or transmission of excessive forces, were responsible for 168 injuries. Fuel system failure at impact, with fire resulting, was responsible for an additional 50 injuries. Aircraft submersion, without occupant escape, contributed 26 additional injuries due to drowning. It was not possible to determine if impact injury was a contributing factor to the inability of the occupants to escape from the helicopter as it was sinking. An additional eleven injuries were attributed to the main rotor blade entering occupied space.

The study indicated that improvements in crash survival would result from improved retention and vertical energy absorption in crew seats and troop seats, from the installation of crash resistant fuel systems, mandating use of restraint systems by all passengers, improving the crash protection of the gunner's belt, and retrofitting emergency flotation systems.

Crash tests of military helicopters. The U. S. Army has continued the helicopter crash test program which had been conducted by the AvSER facility. Six additional tests (at the time of this writing) have been conducted since 1973. These tests have been included in Table 1 as a continuation of the series. The first of these additional crash tests (T-38) was conducted by Lockheed-California Company to assist in validating the "KRASH" computer program (Wittlin, 1973). Program KRASH is a hybrid program that uses nonlinear spring and beam elements and lumped masses in a three dimensional framework to simulate the fuselage structure. The characteristics of the structural elements must be derived from testing or other analysis. The program has been applied to helicopters, small fixed wing airplanes, and large transport airplanes (Wittlin, various citations). It has been used to analyze the results of the drop test of the fuselage section developed under the Bell Helicopter-Textron Advanced Composite Airframe Project (Cronkhite, 1988), and the crash test of the CH-47A helicopter used in Test T-40 (BadriNath, 1978). The other crash tests were conducted by the NASA Langley Research Center. Test T-39 used a CH-47C helicopter to evaluate seven crashworthy crew and troop seats, one standard crew seat, and cargo tiedown loads (Singley, 1976). The seats were:

1. One forward facing two-man and one aft facing four-man troop seat designed by the U.S. Army Agency for Aviation Safety and the U.S. Army Aeromedical Research Laboratory (Haley, 1972). Seat weights were 30 and 52 pounds, respectively. The seats were suspended from the ceiling by wire-bending energy absorbers attached to the seat backs. The seat pans were attached to the floor by one load limiting seat leg and one load limiting diagonal brace under each occupant, and were stabilized by stretchable diagonal cables connecting the rear of the seat pan to the floor. The aft facing seat was provided with stretchable support cables in the seat back to form a membrane type support surface. Both seats were designed to provide 10 inches of vertical stroke at 10 G.

2. A lightweight (14 pound) troop seat designed by Boeing-Vertol (Reilly, 1974). Wire bending energy absorbers connected the seat back to the ceiling, and were designed to provide 14 inches of vertical crash attenuation. Diagonal energy absorbing struts between the front edge of the seat pan and the floor, and stretchable cross cables stabilized the seat and provided energy absorption in the forward direction.

3. A side facing troop seat, developed by Boeing-Vertol for the Naval Air Development Center (Reilly, 1971). The mostly fabric seat was suspended from the ceiling by two wire bending energy absorbers, and connected to the floor by two load limiting struts. The seat weighed 7 pounds.

4. The prototype armored crashworthy crew seat developed for verifying the feasibility of crashworthiness seat design criteria (Desjardins, 1972). This seat was basically a simulated armored bucket attached to parallel guides on a tripod support frame by roller bearings. Vertical suspension of the bucket was by a rolling torus energy absorber. The assembly weighed 211 pounds.

5. An experimental multi-axis armored crew seat. Triaxial energy absorption was provided by three rolling torus energy absorbers. The seat is attached to a vertical guide tube through two sliding collars. The vertical tube is attached to the support frame by a universal joint, and the lower collar on the seat is attached to the top of the support frame by a vertical energy absorber.

6. A multi-axis crashworthy armored UH-1 seat developed by ARA for the U.S. Army Aviation Systems Command (Mazelsky, 1974). The seat bucket is suspended from the seat frame by six rolling torus energy absorbers. It provided only 8.5 inches of vertical energy absorption because it was compatible with the limited cockpit space in the UH-1 and Bell 214 aircraft. The seat weighed 162 pounds.

7. The standard unarmored CH-47C pilot seat. This seat was designed to static loads factors of 8 G longitudinal, vertical, and lateral. It was not designed to crashworthiness standards. It weighed 33 pounds.

The crash environment is given in Table 1. As a result of this test, the aft end of the fuselage collapsed, the floor and belly understructure fractured at station 245, and the engine mass caused the crown structure to collapse until the floor to ceiling height was only 1.75 feet. All seat locations experienced accelerations which were considered to be in excess of human tolerance. The results are summarized in Table 15.

Table 15. Seat Experiments on Crash Test T-39.

Seat	Station	Peak Deceleration, G				Remarks
		x	-x	z	-z	
1:FF Troop Seat						Seat back didn't yield, front leg stroked 7 inches, dummies submarined.
Floor	376	22	9	63	28	
Dummy	370	22	4	37	11	
RF Troop Seat						Diagonal broke, seatback stroked 5 inches, leg stroked 1 inch, dummy G's high.
Floor	394	33	16	118	17	
Dummy	400	24	18	16	6	
2: FF Troop Seat						Seat performed satisfactorily, seatback stroked 6.75 inches, dummy restrained.
Floor	376	22	8	63	28	
Dummy	370	8	1	24	4	
3: SF Troop Seat	246	43	28	87	52	Seat near floor upheaval, seat struck by floor, seat support deformed.
Floor	260	19	16	14	9	
Dummy						
4:Crew Seat	180	--	--	--	--	Seat did not stroke.
Floor	180	--	--	28	21	
Seat Back						
5:Crew Seat	180	--	--	29	13	Seat did not stroke (4 year old energy absorber rusted, it was not protected against rusting).
Floor	180	22	14	48	26	
Seat Back						
6:Crew Seat						Vertical energy absorber stroked, 34 G peak due to seat bucket contact with frame.
Floor	82	--	--	90	37	
Seat Back	82	19	19	34	17	
7:Standard Seat						Dummy restrained, seat transmits injurious force levels.
Floor	82	34	47	109	45	
Seat Back	82	--	--	101	26	

Note: Dashes indicate lost or suspicious data.

It was concluded that:

1. A crashworthy fuselage should maintain a protective shell for the occupants during a crash.

2. Landing gear should be designed to absorb crash energy by stroking over the available distance. Failure of the gear should not result in penetration of the occupant compartment or flammable fluid containers.

3. Energy absorbing seats can increase occupant protection with little increase in weight.

4. Twelve inches of seat stroke should be provided. One crew seat showed the consequences of too little stroking distance when it produced an acceleration of 34 G after bottoming.

5. Partially occupied multiple place seats generate problems with crash force attenuation. Single occupant seats are preferred.

6. Wire bending energy absorbers performed well. Rolling torus type energy absorbers should b protected from the environment to prevent rusting.

The next test, T-40 (also a CH-47A) was conducted on August 4, 1976. It represented a 95th percentile potentially survivable crash. Both left and right fuel cells burst as soon as ground contact with the fuel pods occurred, resulting in a spray which enveloped the helicopter. All major concentrated mass items (hubs, shafting, transmissions, engines, etc.) maintained structural integrity throughout the crash. Both aft landing gears failed upon ground contact. The aft pylon area was intact and the aft ramp opening provided sufficient space for emergency egress. Both pilot and copilot seats were not crashworthy, and showed seat pan failures. Most of the structural damage was due to crushing of the underfloor structure with intrusive failure of the floor panels in the center fuselage area. Extensive damage occurred around the main landing gear support structure. These structural failures allowed the landing gears to rotate into the main fuel pods. The KRASH computer model was used to analyze the structural failure mechanism in this test (BadriNath, 1978).

Crash test T-41 was conducted on July 8, 1981 (Smith, 1986). The YAH-63 helicopter used in this test was one of three prototypes built by Bell Helicopter Textron for the

AAH procurement. It was a twin engine attack helicopter with tandem seats for two crew members. The forward cockpit was modified to resemble the AH-64 cockpit, and was equipped with a production AH-64 crashworthy crew seat. The seat is mounted on the bulkhead through roller bearings engaging steel guide tubes which restrict its motion to the vertical direction only. It is designed to stroke 12.3 inches at 14.5 G, using inversion tube energy absorbers in tension. The seat weighs 136.6 pounds, including boron carbide armor. The seat in this test was equipped with a prototype inflatable body and head restraint system (IBAHRS). The rear aft seat was the standard YAH-63 crashworthy, bulkhead mounted, pilot seat. It was designed to stroke 12 inches at 14.5 G using inversion tube energy absorbers in compresssion.[Note 6] The actual impact conditions deviated considerably from those planned because of an over estimation of aerodynamic drag and because of prevailing wind conditions at the time of the drop. The resultant impact velocity was 60.1 f/s rather than 50 f/s. The crash pulse contained 44 percent more energy than was planned. All three landing gear over-pressure valves opened at impact. After stroking of the main gear, the fuselage crushed approximately 5.5 inches. The high mass items in the helicopter received peak accelerations of between 30 and 64 G, but were, nevertheless, retained in place with no measurable deformation at their mounting locations. The fuselage absorbed the impact without major structural damage that might have been hazardous to the crew. The crash environment reached 54.5 G at the location of the forward (AH-64) seat and 38 G at the aft pilot (YAH-63) seat. The AH-64 seat stroked at between 14 and 19 G until bottoming with a 31 G peak acceleration. Both of the energy absorbers in the YAH-63 seat buckled after stroking only 2.5 inches. Nevertheless, the seat continued to absorb energy and limited the peak vertical seat acceleration to only 17 G. (Performance of the IBAHRS was discussed in an earlier section.) The performance of the crashworthy fuel system was satisfactory, with only one small leak resulting from the fracture of an aluminum flange by a non-standard mock-up ammunition tray.

Crash tests T-42 and T-43 demonstrated the crash survivability of all composite airframes developed by Bell Helicopter Textron (the Bell D-292) and Sikorsky Aircraft (the S-75) under the U.S. Army Advanced Composite Airframe Program. At the time of this writing, final reports of the crash results have not yet been released. It is understood that both tests were successful in terms of occupant survivability, but that additional work is warranted in the area of landing gear to fuselage attachment structure.

CIVIL AIRCRAFT CRASHWORTHINESS.

The increasing progress in military crashworthiness which yielded the Crash Survival Design Guide and the military specifications for aircraft crashworthiness in the early 1970's was paralleled by a an apparent lack of progress in civil aviation crashworthiness. Attempts to promote crashworthy features for aircraft had not met with success in the market. A recommendation by the U.S. National Transportation Safety Board in 1964 that shoulder harnesses should be required for all occupants of newly certified general aviatioin aircraft was met by Federal Aviation Administration response that there was not sufficient justification for such a requirement (Snyder, 1978). Such a rule was finally issued in 1978. In 1975, a committee of the Society of Automotive Engineers attempted to develop an Aerospace Recommended Practice for improved seat and restraint systems for small aircraft. The recommendation was disapproved, and the committee was disbanded by the SAE (Snyder, o.c.). A growing trend to litigation in the U.S. had the effect of closing much previously open discussion on improving the crashworthy design of aircraft.

Still, some progress was made. Cessna Aircraft Company installed a small impact test facility, conducted seat and restraint system tests, and crashed small airplanes into a barrier (Bloedel, 1972). The FAA Atlantic City facility conducted impact tests of various restraint systems (Daiutolo, 1972; Sommers, 1973). Bell Helicopter Textron produced energy absorbing seats for the Model 222 helicopter in 1980. This development was followed by energy attenuating crew seats for the Model 214 ST and Model 412 helicopters (Fox, 1989).

Chandler, having taken over the management of the FAA Civil Aeromedical Institute (CAMI) Protection and Survival Laboratiory after Swearingen's retirement in 1971, initiated a program of cooperative dynamic testing with various activities responsible for seat and restraint system design. This program grew out of a concern that much of the civil aviation community, including manufacturers and the FAA, had not recognized the benefits of dynamic test evaluation for improving the crash protection of aircraft seat and restraint systems. Instead, the concept of many was that seat and restraint crashworthiness was synonymous only with increasing seat strength or restraint system strength. This, in turn, was viewed as equivalent to increasing seat weight and cost. Neither of these outcomes was considered acceptable. Perhaps more of a problem, attempts to increase seat strength sometimes resulted in increased seat rigidity. Increased seat rigidity led to more frequent seat failures in crashes, and to the mistaken conclusion that attempts to improve seat crashworthiness were impractical.

The goal of the CAMI program was to create an operating environment where both the industry and the FAA could learn methods for improving the crash performance of civil aircraft seat and restraint systems. Early participants in this program were Piper Aircraft, who developed an energy absorbing seat for light aircraft (Underhill, 1972) (Figure 26) and NASA Ames Research Center, who proposed a concept of individual energy absorbing seats, with shoulder belts, for large transport airplanes.[Note 7] Gradually, the program grew to include cooperative tests with the military services and the U.S.

National Highway Traffic Safety Administration as well as the civil aviation community (e.g., Chandler, varoius citations). As the program progressed, the usefullness of dynamic testing as a tool for detecting structural seat problems and for demonstrating crash protection became better understood. Several changes were incorporated into production seats to improve their performance beyond that required by the regulations. Experience in the test methods used in evaluating seat and restraint systems for military crashworthy aircraft led to a better understanding of the potential application of those methods to civil aircraft systems. Often it was found that redesign of some minor fitting or joint which broke in a dynamic test would significantly increase the crashworthiness of a basic seat design. Eventually, this understanding was sufficient to support the first significant general applications of crashwortiness technology to civil aircraft.

The NASA-LaRC Crash Tests and Seat Development Program. In August, 1972, a hurricane caused extensive flooding of several areas in the United States. The Piper Aircraft Corporation plant in Lock Haven, Pennsylvania, near the Susquehanna River, was flooded. Many completed airplanes outside the plant, and others under construction inside the plant, were submerged in the flood. After the flood, it was decided that these airframes could not be made reliably airworthy. Instead, 35 Piper Navajo, Aztec and Cherokee airframes were made available to the Federal Aviation Administration and the National Aeronautics and Space Administration for non-flight research. These low wing airframes were supplemented by high wing (Cessna 172) airplanes made available by the FAA.

These airframes were used in a NASA/FAA general aviation crash dynamics program conducted at NASA's Langley Research Center (LaRC). A large gantry had been built at the Center in the early 1960's to allow simulation of the lunar excursion module landings on the moon. With the conclusion of that work, the facility became available for other projects. It was modified to become a swing framework for conducting crash tests on aircraft weighing less than 13 600 kg (30 000 lb), and renamed the Langley Impact Dynamics Research Facility (Vaughan, 1976), (Figure 27). The gantry is 73 m high and 122 m long, with supporting legs spread 81 m apart at the ground and 20 m apart at the 66 m level. A strip of reinforced concrete 122 m long, 11 m wide and 0.2 m thick provided the impact surface for all but two of the tests. For the tests, an aircraft was suspended from the top of the gantry by two swing cables and then drawn back above the impact surface by a pull back cable. When the aircraft was released from the pullback cable, it swung towards the impact surface. The swing cables were separated from the aircraft just prior to impact to free it from restraint. For tests requiring flight path velocities in excess of 26.8 m/s, it was necessary to add small rocket engines to the aircraft to supplement the force of gravity. Since these rocket engines would burn out before impact, they did not change the crash conditions other than the increased velocity.

The crash test program was initiated in 1973 (Hayduk, 1979, Alfaro-Bou 1975). The objectives of the program were to determine the effects of impact speed, flight path angle, roll angle and ground condition on the dynamic response of the airplane structures, seats and occupants during simulated crashes in which the airplane structure retained sufficient cabin volume and integrity to permit occupant survival. The crash tests conducted under this program are shown in Table 16. The nominal values of the roll and yaw angles (not shown in the table) were essentially zero for all tests except 9 (30° L roll), 10 (15° L roll), and the second (11.5° R yaw) and third (18.6° R roll) FAA sponsored tests. Details of each test can be found in the references cited in the table.

The concrete impact surface provided a reproducible impact condition in all but two of these tests. Typically, an aircraft would impact this surface, crush, rotate, and then slide until it came to a stop. This test sequence generated longitudinal (x axis) crash pulses which consisted of an approximately triangular shaped primary impact followed by a long secondary deceleration of relatively low magnitude until the airplane stopped. The slide out distance varied from approximately 14 m to 140 m. The average coefficient of friction measured during the slide out was 0.42 (Thompson, 1984). The normal (z axis) crash pulse typically consisted only of a single triangular shaped impact. The crash pulse data in the table describes only the triangular shaped portion of the impact pulse along the normal and longitudinal axis (Carden 1982; Thompson 1984). No compensation was made for the slide out deceleration portion of the longitudinal impact pulse. Thus, the longitudinal crash pulse data shown in the table are lower than would be expected if all of the crash energy had been expended in the primary triangular shaped impact pulse. The crash conditions in tests 4, 6, 12 and FAA-2 produced only minor structural damage to the airframe. The airplane used in test FAA-2 was repaired and used again for test FAA-4. Transient roof collapse, i.e., a loss of cabin volume during the crash which was not maintained after the crash, was observed in the more severe tests.

Two tests (11 and FAA-4) were conducted by impacting aircraft on a soil test bed approximately 12.1 m wide, 24.4 m long, and 1.2 m deep placed over the concrete pad. The soil was compacted to represent a plowed farm field; that is, it was firm enough to support a light tractor with pneumatic tires but soft enough to allow an airplane to dig into the soil during a crash. In both of these tests, the airplane dug into the soil and stopped without significant slide out. The livable volume (i.e., the volume sufficient to maintain space between the occupants and the structure) was compromised in both tests. Longitudinal decelerations in these tests showed major increases when compared to similar tests on the concrete impact surface, but normal decelerations either decreased or showed no change.

Careful review of the data from this test program, and the earlier program conducted

TABLE 16. NASA and FAA CRASH TESTS CONDUCTED AT NASA/LaRC

Test	Aircraft and impact surface[1]	Crash Velocity, m/s[2] V_R	V_V	V_H	Aircraft pitch angle, degrees	Primary Aircraft Crash Pulse[3] Maximum -G z	x	Duration ms z	x	Velocity Change m/s z	x	References	Tests
1	t;u;l;c	12.7	3.6	12.1	-12								
2	t;u;l;c	26.7	7.4	25.6	-12	20	19	89	60	8.5	6	Alfaro-Bou (1977)	1,2
3	t;u;l;c	26.2	8.4	24.8	-18	28	18	50	44	8.7	4.3		
4	t;u;l;c	27.4	7	26.5	4	16	7	102	101	8.5	5	Castle (1978)	1,2,6,7,8,9, 10
5	t;u;l;c	26.1	9.1	24.4	-19.5								
6	t;u;l;c	26.9	7.6	25.8	14	18	8	110	110	10.4	3.1	Hayduk (1979)	2,3,4,6,10
7	t;u;l;c	28.6	21.1	19.3	-47.25	20	8.8	174	144	20.7	4.6;		
8	t;u;l;c	27.6	13.8	23.9	-31	18	16	135	110	13	6	Castle (1979)	2,9,10
9	t;u;l;c	26.3	7.3	25.3	-13								
10	t;u;l;c	27.8	8.6	26.4	-14							Vaughan (1979)	2,4,6
11	s;u;l;s	25	12.9	21.4	-27	12	28	132	138	10	17.7	Alfaro-Bou (1981)	2,4,6,8,11, 12,13,15,16, 17,18
12	s;u;l;c	25	6.5	24.1	9	12	4	149	60	9.5	1.2		
13	s;u;l;c	25	12.1	21.9	-26	27	11	49	93	13	5		
14	t;p;l;c	32.7	9.5	31.4	-11.75								
15	t;p;l;c	41.4	12.7	39.3	-12	46	16	64	58	17	5	Williams (1982)	18,19,20,21
16	t;u;l;c	40	10.4	38.6	-4	46	12	54	62	15	4	Castle (1983)	11,12,13
17	t;p;l;c	40	20	34.6	-38	42	22	97	68	19	10		
18	t;u;l;c	27.9	13.9	24.2	-31	27.2	15.2	83	90	11.3	8.2	Carden (1984)	22,23,24
19	t;u;l;c	27	7	26.1	-17.7	16	5.5	120	88	10.6	4		
20	t;u;l;c	26.6	7.1	25.6	2	31	6.4	57	52	9.1	1.9	Thompson (1984)	2-21
21	t;u;l;c	27.1	13.6	23.5	-29.5	29.9	14	96	112	12.3	10.5	Carden (1982, 1983)	2-21 FAA 1-4
22	t;l;p;c	33.7	8.7	32.6	0								
23	t;l;p;c	36.4	9.4	35.2	1.2								
24	t;l;p;c	37.9	9.8	36.6	2.5								
Additional FAA sponsored tests													
1	s;h;u;c	25	12.5	21.6	-32	21	22	120	110	11	8	Vaughan (1980)	1,2,3,4
2	s;h;u;c	23	6.7	22	13.5	7	3.5	160	60	6	1.5	Alfaro-Bou (1981)	1,2
3	s;h;u;c	25.9	14.7	21.3	-39	18	17	120	130	13.8	12	Thompson (1984)	1,2,3,4
4	s;h;u;s	25.3	13.9	21.4	-34.5	18	45	130	100	14.8	21.5	Wittlin (1979)	1,2,3,4

Note 1: Designations in this column represent twin (t) or single (s) engine aircraft, low (l) or high (h) wings, pressurized (p) or unpressurized (u), and impacted on concrete (c) or soil (s).
Note 2: The vertical (V_V) and horizontal (V_H) components of the resultant impact velocity (V_R) are shown.
Note 3: The maximum deceleration, duration and velocity change generated in the primary impact pulse as determined along the aircraft normal (z) and longitudinal (x) axis as determined by Carden (1983) are shown here.

by NACA, indicated that the primary impact pulse was, effectively, triangular in shape. (Prior analysis of the NACA data was based on the understanding that the crash pulse was composed of a base pulse and a superimposed high-G impact.) This finding greatly simplified the analysis of the data. It was now possible to correlate the maximum acceleration with the change in velocity, as shown in Figures 28 and 29 (Carden, 1983).

Many types of seat and restraint problems were observed during the series of full scale crash tests. High loads generated by combined vertical and horizontal decelerations caused seat tracks, seat legs, and track attachment fittings to break or separate. Seat legs "punched through" weakly supported track. Fuselage or seat deformation during the crash caused either high restraint forces or excessive slack in the restraints when the restraint system was attached to the fuselage rather than the seat. Seat pans made of sheet rubber were found to tear prematurely, and allow the dummy to break through the pan and contact inner seat frame structure or the aircraft floor. Restraint system buckles which had passed stringent static tests were observed to release during the crash. An inertia reel did not lock, and allowed the dummy's head to impact the interior. Seat deformation was observed to release the seat locks from the floor track, allowing the seat to slide forward.

The program of controlled crash tests was supplemented by development efforts to improve seat and floor structure performance. Subfloors with energy absorbing capability generated by corrugated beam/notched corner, corrugated half shell, notched corner, foam filled cylinder, and canted bulkhead concepts were constructed and tested. The concepts using corrugated beam with notched corner structure and notched corner structure alone were selected for full scale test. In the full scale crash tests (Tests 22, 23 and 24), floor decelerations were reduced almost 50% by the better performing corrugated beam with notched corner design subfloor, and intrusion into the liveable cabin volume was reduced.

Three types of energy absorbing seats were also installed for these tests. The pilot seat was a prototype of an energy absorbing seat being developed by Jungle Aviation And Radio Service (JAARS), a missionary organization. The front legs of this seat were S-shaped and the rear legs were slanted forward to provide vertical energy absorption by bending. A passenger seat was an early experimental version of a seat designed for use in helicopters (Fox, 1983). The seat bucket in this seat was designed to traverse down two vertical guides, crushing a vertically oriented composite tube as it absorbs energy. A second energy absorbing passenger seat (Alfaro-Bou, 1981) was developed by NASA-LaRC. In this seat, a wire-bending energy absorber is placed as a diagonal link in a parallelogram seat-leg linkage system. The diagonal link moved upwards into the seat back as the seat pivoted forward and downward on the four-bar parallelogram linkage leg arrangement.

The seats absorbed energy in all tests, stroking from 6.6 cm. to 16.5 cm. Breaks occurred in the legs of the pilot seat as the seat stroked downward. While the lap belt portion of the restraint was attached to the seat, the shoulder belt was attached to the overhead roof structure. As the seat moved downward, the shoulder belt pulled up on the lap belt, causing high restraint loads, and allowing potential submarining of the seat occupant. The experimental helicopter seat, which allowed only vertical movement during energy absorption, moved through the maximum stroke distance (15.2 cm.) in all three tests. Since the aircraft floor was deformed during the crash, this introduced bending and misalignment into the load-limiting mechanism, and caused eccentric loads on the composite energy absorbing tube. The eccentric loads crushed only one side of the composite tube, leading to an excessive stroke at reduced stroking force. The NASA-LaRC seat appeared to function as intended, and accommodated non-symmetric loading due to the floor deformation. The lowest floor accelerations and consequently least seat stroking occurred with the load limiting subfloors, where the greatest crushing of the subfloor took place. The modified subfloors also minimized the floor deformation in the cabin.

Initially, this NASA-LaRC seat development effort considered three load limiting seat concepts (Fasanella, 1979) (Figures 30 through 32). A ceiling suspended seat similar in design to a helicopter troop seat (Reilly, 1974), used two wire-bending type energy absorbers to suspend the seat from the cabin ceiling, and two energy absorbers located diagonally between the front of the seat and the floor at the rear (Reilly, 1979). Lateral loads were resisted by a pair of crossed stainless steel cables which connected the front of the seat to the floor and a pair of parallel cables at the rear of the seat pan which stretched to the floor. The second concept was a floor mounted seat which used a pivoted parallelogram linkage to support the seat. An energy absorber was located along the short diagonal of the parallelogram. The third concept used a rigid seat bucket which was mounted on legs designed so that the seat would rotate from an upright position to a reclined position during a crash. Energy absorbers located at the bottom of the legs were intended to control the motion of the seat.

These seats were tested by the CAMI in 1978 (Fasanella, o.c.). These sled tests duplicated the seat orientations called out in the Crash Survival Design Guide but provided an impact pulse of 34 G's at 13 m/s for Test 1 (combined vertical and forward loading) and 24 G at 15 m/s for Test 2 (combined forward and lateral loading). Both floor mounted seats exhibited a number of hardware malfunctions in the tests which indicated a need for additional development work. The seat which was suspended from the ceiling showed significant reductions in occupant accelerations in both tests. However, this concept was ultimately considered unsuitable for most small aircraft because of the necessity of a strong roof structure which maintains adequate clearance above the cabin floor during a crash.

Continued development of the parallelogram linkage seat resulted in an improved design which allowed a 26 cm vertical stroke for energy absorption. To achieve this increased stroke distance, the energy absorbers were allowed to stroke into clearance space within the seat back, as previously described. This seat, together with standard and modified standard seats, and two different types of JAARS energy absorbing seats (to be discussed separately) were static tested and drop tested at NASA-LaRC and dynamically tested by CAMI (Alfaro-Bou, 1985). The dynamic sled pulse selected for the testing at CAMI represented a vertical impact with -34 degrees pitch and had a sled impact velocity of 42 f/s, peak sled deceleration of 29 G, and an impact pulse duration of 0.09 seconds. Only the NASA-LaRC parallelogram seat and the two JAARS seats showed no significant damage in these tests. Compression forces were measured at the base of the lumbar column in the dummy used in these dynamic tests. The NASA-LaRC seat and the JAARS crew seat limited this compression load to less than 1500 pounds, but the other seats generated compression forces at the base of the dummy lumbar column which ranged up to 4000 pounds.

The JAARS/MAF Retrofit Crash Protection Program. The Jungle Aviation And Radio Service (JAARS) and Mission Aviation Fellowship (MAF) are inter-denominational missionary organizations which operate a fleet of approximately 120 aircraft, mostly single-engine airplanes. Operations are conducted in about 30 countries, primarily in under-developed areas where ground transportation is absent or inefficient. It is estimated that, on the average, over a 24 hour period, a JAARS or MAF plane takes off every four minutes. These organizations had provided upper torso restraint systems for crew and passengers, had installed extra tie-down fittings for cargo, had installed fire extinguishers in their airplanes and had required the use of helmets by pilots in an attempt to provide crash protection. Nevertheless, their fatality ratio in crashes had not shown significant improvement over that of the U.S. general aviation fleet.

In 1978, they formed the Mission Aviation Crashworthiness Committee to look for ways to improve the crash survivability of their aircraft. After a preliminary study, it was decided that seats and a seat frame interface would be developed by JAARS for the Cessna 206 and Helio Courier airplanes, and by MAF for the Cessna 185. Cabin reinforcement kits, engine tie down, anti-scooping structure, and fuel spillage control devices would be developed by contractors. Dynamic tests of the seat and restraint systems were provided through NASA-LaRC and CAMI. The results of this program are summarized by Siahaya (1987).

Three basic seat types were investigated in this program. The crew seat was provided with S-shaped front legs and slanting rear legs for energy absorption in the vertical direction. The lap belt was attached to the seat frame, and an inverted Y dual shoulder belt system was designed to be attached to reinforced roof frames or the overhead spar at the upper end. The lower end joined the lap belt near it's attachment at the back of the seat pan. A passenger seat had similar design, except that the seat legs could be folded inward. Lateral loads in both of these designs were controlled by diagonal steel cables between the seat pan and the lower legs. The seats were fabricated of chrome-molybdenum alloy steel tubing, normalized and stress relieved after welding. Tightly wound coil springs were placed in the tubes which formed the S-shaped legs to keep the tube walls from collapsing during stroking of the seat. Medium duty floor track, similar to that used in most large transport airplanes, was used to attach the seats to the cabin floor. A second passenger seat concept, for the rear seats in the airplane, consisted of a rigid polyvinyl foam block, four inches thick but tapered to the rear, contained in an aluminum sheet metal pan which, in turn, mounted to the floor track. A number of holes were cut in the block from top to bottom to adjust it's crush characteristics. The top surface of the block was covered with a thin aluminum sheet The seating surface of all seats was covered by a 25 mm (1 inch) thick cushion made of firm, rate sensitive open cell foam.

Forty-four dynamic tests were conducted on the seats, including fifteen drop tests and two full-scale aircraft crash tests at NASA-LaRC. Twenty-nine fully instrumented sled tests were conducted by CAMI, at impact levels up to 31 G. These tests indicated that the attachment of the upper torso restraint system to overhead structure could limit the vertical energy absorption capability of the seat, and showed that the attachment fittings between the seat and the floor track could limit the forward deceleration capacity of the system to between 19 and 23 G. In one 22 G, 31 fps test which simulated a vertical impact with the floor pitched downward at 30 degrees, the compression force at the base of the dummy lumbar column was only 1520 pounds. This was accomplished with post-test deformation of 1 inch on the right side and 1 7/8 inches on the left hand side of the seat. The foam block seats performed well under 19 G impacts, but tended to break into small pieces and allow the dummy to "bottom out" at higher decelerations. Difficulty was observed in keeping the pan of the foam block seat attached to the floor track if the floor was deformed. It was reasoned that the distance between the front and rear stud track fittings would shorten as the pan was distorted, and that the unlocked stud would become disengaged from the track. It was also observed that, as the foam blocks crushed, the lap belt was no longer held tightly against the pelvis, thus increasing the chance for submarining.

Civil Rotorcraft Accident Analysis. Simula, Inc., conducted a study for the Federal Aviation Administration to evaluate impact conditions and injury producing mechanisms in civil rotorcraft crashes (Coltman, 1983, 1984, 1985, 1986a). Records of 1,351 rotorcraft accidents which occurred from 1974 through 1978 were examined. Of these, 311 accidents were found to have data which could be used to estimate the impact conditions. Crash scenarios for these accidents are listed in Table 17.

Table 17. U.S. Civil Rotorcraft Crash Scenarios Studied

Accident Category	Number of Accidents	Number of Occupants	Fatal and Serious Injuries
High vertical impact velocity	70	163	29
High longitudinal impact velocity	21	35	4
Rollover	34	82	5
Wire strike	25	31	14
Water impact	24	67	24
High yaw rate	21	37	3
Unknown	63		
All Other	53	82	18

Of the 311 accidents, 211 were survivable, including 57 accidents of low severity. Primary emphasis in the study was placed on the remaining 134 survivable but severe accidents. The typical pitch, roll, and yaw angles at impact in these accidents were small. Eighty-one percent of rotorcraft impacted the ground with pitch angles of ±15 degrees or less, 78 percent with roll angles below ±5 degrees, and 89 percent with yaw angles below ±10 degrees. For these severe but potentially survivable crashes, the 95th percentile vertical impact velocity was 26 f/s, longitudinal impact velocity was 50 f/s, and lateral impact velocity was 10 f/s. It was noted that the 95th percentile vertical impact velocity (26 f/s) was considerably less than that found in studies of U.S. Army helicopters (42 f/s) or U.S. Navy helicopters (38 f/s). This was attributed to differences between military helicopter and civil helicopter operational missions.

The 95th percentile levels were judged to represent the upper limits of crash survival for the U.S. rotorcraft fleet, even though serious and fatal injuries occurred in crashes well below those levels. A comparison of injuries received while wearing lap belt and shoulder harness restraint versus wearing only a lap belt restraint showed no significant difference in those crashes having a primarily vertical impact. However, in survivable crashes with predominantly longitudinal impacts, the use of lap belts and shoulder harnesses eliminated serious and fatal injuries. It was concluded that, for well restrained occupants, only the vertical forces exceeded the levels which would produce serious injuries.

The National Transportation Safety Board General Aviation Crashworthiness Project. Between 1972 and 1982, 36,500 small airplane accidents involving 76,600 occupants occurred in the United States. Sixteen percent of the occupants were killed, and nine percent were seriously injured (Clark, 1987). Investigation of these accidents indicated that many of the fatal and serious injuries could have been prevented if crashworthy seat and restraint systems were used. In 1980, the National Transportation Safety Board (NTSB) began to plan a "General Aviation Crashwortiness Program" to provide data for improving crashworthiness of small airplanes.

The field investigation phase of the program began January 1, 1982, concurrent with the introduction of an expanded NTSB accident/incident report form. This new form, like that developed by the Crash Injury Project in the late 1940's, (Hasbrook, 1951) provided a means of systematically reporting data on crash kinematics, occupant survival and injuries, seat/restraint system performance and fuselage structural crashworthiness. Analytical techniques were developed to use these data to estimate the impact severity of the crash, and these techniques were validated by comparing the post crash field measurements of aircraft crashed in the NASA-LaRC test program with the data collected on the crashes (NTSB, 1983).

For the second phase of the study, the NTSB used data available in 535 reports of accidents that occurred in 1982 to perform a detailed analysis of crash kinematics and occupant injuries (NTSB, 1985a). Accidents selected for this study were general aviation airplane crashes in which at least one occupant was fatally or seriously injured. Accidents involving aerial application airplanes, home-built airplanes and older airplanes of tube and fabric construction were excluded. There were 1,286 occupants in these airplanes. In 391 fatal accidents, there were 859 fatalities, 74 occupants with serious injuries, and 19 occupants with minor or no injuries. All occupants were fatally injured in 85 percent of these crashes. In 144 non-fatal accidents, 228 occupants were seriously injured and 87 occupants received minor or no injuries (one occupant's injuries could not be determined).

Impact severity was defined in terms of estimated impact angle and velocity, and each accident was defined as survivable or not survivable. It was found that the impact severity increased with impact angle because the velocity change during the initial principal impact becomes greater at higher impact angles. It was found that over three-fourths of the survivable accidents and only 14 percent of the non-survivable accidents occurred with impact speeds of less than 90 knots and impact angles of less than 45 degrees. The findings indicated that a boundary of survivable impacts for these crashes could be defined. This boundary began at a 75 to 90 knot impact speed with 0 degrees impact angle, passes through the 60 knot and 45 degree point, and terminated with a 45 knot impact speed and 90 degree impact angle. Those non-survivable crashes in the lower speed range involved inverted impacts or direct impact with trees or other fixed objects.

In the survivable crashes, occupants wearing shoulder harnesses received less serious head and upper body injuries than occupants without upper torso restraint. Shoulder harnesses did not reduce injuries to the lower torso or to the extremities. Only 40 percent of the airplane occupants in this study had shoulder harnesses available, and only 40 percent of those occupants were wearing the shoulder harness at the time of the crash. The potential for benefit could be established for 800 fatally injured and 229 seriously injured occupants. It was estimated that 13 percent of the 800 fatally injured occupants could have survived with serious injuries, while an additional 7 percent could have survived with only minor or no injuries if they had been using a shoulder harness during the crash. Approximately 88 percent of the seriously injured occupants would have received only minor or no head or upper torso injuries if shoulder harnesses had been worn. It was also estimated that 2 percent of the fatalities and 34 percent of the serious spinal injuries could be prevented by energy absorbing seats.

In the third phase of this study, NTSB analyzed 39 additional general aviation crashes to estimate the limits of accelerations and velocity changes in survivable crashes (NTSB, 1985b). From studies of airframe damage and the severity of injuries, longitudinal velocity changes of 60 f/s were estimated to approach the upper limits of the survivable crashes. At this upper limit, airframe crushing and shoulder harness performance often allowed the occupants to contact the instrument panel. In the normal (vertical) direction, the upper limit of survivable airplane acceleration approached 25 to 30 G, with velocity changes in the order of 50 to 60 f/s. Table 18 compares the data from the second and third phases of the program.

Table 18. Comparison of Data between Phase II and Phase III of the NTSB General Aviation Crashworthiness Project

	Phase II	Phase III
Accidents	525	39
Occupants	1,268	118
Survivable Crashes	59 %	97 %
Fatally injured occupants	800	27
Fatally injured occupants in survivable crashes	216	23
would have survived with shoulder harness use	75 %	65 %
Seriously injured occupants	229	65
would have benefited from use of shoulder harness	88 %	77 %
would have benefited from energy absorbing seats	34 %	24 %
Occupants with minor or no injuries	87	27
Shoulder harnesses available	40 %	32 %
Shoulder harness use when available	40 %	45 %
Overall shoulder harness use	16 %	14 %

In one crash with energy absorbing seats, a 270 pound occupant suffered fatal injuries when his seat bottomed out, while a 180 pound occupant whose seat did not bottom out received serious injuries. Failures of steel cables, inserted as links between the restraint system and the airframe were observed. Forty-four percent of the occupied seats broke loose from the airplane structure during the crash. Seat feet or legs broke or separated. Lateral loads, impacts from occupants seated behind the seats, and floor warping were identified as contributing factors. The performance of seats which provided vertical energy absobing capability was limited by inadequate stroking distance or items located under the seats, sometimes installed by the owner. Fabric seat pan material demonstrated low resistance to tearing when stressed as a membrane. Neoprene seat pan material apparently deteriorated with age and separated from its attachments to the seat frame during relatively minor crash loading. Field modifications of seats were found to contribute to seat problems. Drilling additional holes in highly stressed seat components, adding additional items of mass (such as fire extinguishers) to the seat frame, and inadequate repair of seat pans (replacement of the seat pan membrane with "lawn chair webbing which was fastened by the kind of staples used for paper") contributed to these problems.

The data collected in the second phase of the study included 128 crashes involving fire. These accidents involved 298 occupants, with 249 fatal injuries and 13 surviving occupants with serious thermal injuries. By eliminating those fatalities which could be attributed to acceleration trauma (severe impact, no soot in the trachea, significant blunt trauma injury), it was estimated that 32 to 44 lives could have been saved if fires had been prevented. By grouping the crashes according to severity and comparing fatality rates in each group in fire and non-fire crashes (and correcting the analysis for accidents where impact data were not available), it was estimated that 32 fatalities were caused by fire in 1982. It was concluded that 14 percent of the deaths in fire accidents could have been saved if there had been no fire. This would indicate that about 4 percent of the overall fatalities were related to fire. In addition, it was estimated that serious injuries could be reduced by about 6 percent if fires were eliminated.[Note 8]

The General Aviation Safety Panel. In response to a challenge by the FAA Administrator, a panel of 13 representatives from the general aviation community was formed for the purpose of recommending regulatory and non-regulatory ways by which the FAA could promote general aviation safety (Olcott, 1983). These people represented the senior management from aircraft manufacturers, operators, and insurers, organizations representing owners, pilots, home builders, aircraft safety foundations, and publishers dedicated to the general aviation community. The group, which became known as the General Aviation Safety Panel (GASP), met three times between August and November, 1982, and addressed the major factors that contribute to fatal accidents in small airplanes. Short range goals which could be acted on immediately, and long range goals which could be implemented within 12 to 18 months were considered by the Panel. They eventually chose to concentrate on four topics: weather, training, crashworthiness, and dissemination of safety information. Specific findings and recommendations in each of these areas were submitted to the FAA on February 9, 1983. In support of the crashworthiness recommendations, the General Aviation Manufacturers Association (GAMA) recommended as long term goals: "Collect data for at least one year on general aviation accidents to obtain information on the effectiveness of current seats and restraints. ... Determine the dynamic limits of current seat designs (designed for 9 "G" static loads). Establish a correlation, if any, between static tests and dynamic loads. Establish a basis for design criteria in terms of dynamic loads with emphasis on acceleration pulse shapes and duration."

In response to these recommendations, the FAA requested that the GASP develop specific recommendations to improve crashworthiness. A preliminary meeting was held in July, 1983 to define the scope and goals for that effort. The conclusions of that meeting were:

a. The FAA should mandate the installation and use of shoulder harnesses for all newly manufactured small airplanes.

b: The FAA should consider ways to facilitate the installation of shoulder harnesses in older aircraft.

c. Revised specifications for restraint systems with shoulder harnesses should be developed.

d. A technical working group should be formed to prepare a detailed proposal for occupant protection in small airplanes which would provide a quantitative definition of the crash event (and a means for achieving that environment) and the occupant environment that must be maintained during the crash event. This proposal should be submitted in time for FAA Airworthiness Review scheduled for May, 1984.

e. Fuel system crashworthiness should be addressed after the occupant protection effort was concluded,

f. Additional education was needed regarding dynamic tests, computer modeling, and the role of composites in crashworthy design.

Since the final recommendations of the working group eventually formed the basis for new regulatory requirements for small airplane seating and restraint systems and were used as a model for similar new requirements for transport and helicopter seating systems, the development of those recommendations will be discussed in detail. The first formal meeting of the working group took place in September, 1983.[Note 9]

The group met formally at one month intervals. Following the general approach outlined in the U.S. Army Crash Survival Design Guide, they reviewed several dynamic test conditions. The results of the NASA Langley Research Center (NASA-LaRC) crash tests of general aviation aircraft (previously described), the FAA sponsored study of civil rotorcraft accidents (Coltman, 1984, 1986) and the National Transportation Safety Board (NTSB) three phase study of general aviation crashworthiness (Clark, 1987; NTSB, 1983-1985) were used to define crash environments. Injury criteria, based on automobile and ejection seat research, were reviewed. Computer modeling was used to estimate the seat stroke required to limit spinal injuries.

The determination of suitable dynamic test conditions was one of the first topics considered by the working group. For the first meeting, crashes bounded by the velocity changes suggested for military helicopters (42 f/s vertical, 25 f/s lateral, and 50 f/s longitudinal, with a resultant velocity vector of 50 f/s or less) were suggested by the chairman. NASA-LaRC suggested a test in which a 29 G, 42 f/s triangular shaped vertical impact pulse would be applied to a seat pitched downward 30°. It was estimated that the seat must stroke 7 inches in this test. Simula, Inc., recommended three test conditions; a 33 G, 35 f/s vertical impact, a 50 f/s longitudinal impact having a trapezoidal pulse shape with a 16 to 20 G plateau, and a 40 G, 40 f/s vertical impact with the seat pitched downward 30° and rolled 10°. Again, it was estimated that the seat should stroke 7 inches in the vertical test. The FAA indicated they were considering impacts with 50 f/s longitudinal velocity, 30 f/s vertical velocity, and 20 f/s lateral velocity. After considerable discussion, it was decided that testing could be limited to two tests. A vertical impact with a triangular pulse shape providing a velocity change between 25 and 34 f/s with a duration of 0.065 to 0.1 seconds, and a 23 G longitudinal impact with a velocity change of 50 f/s were proposed for study before the next meeting. The effects of pulse shape and yaw in the longitudinal test were to be evaluated.

NASA-LaRC and Simula, Inc. presented results of parametric studies of the impact pulse at the October meeting of the Working group (Soltis, 1985). NASA-LaRC evaluated two tests; a 50 f/s longitudinal impact with a trapezoidal pulse shape having a 23 G plateau and a maximum onset slope of 1440 G/s, with the seat yawed 10° from the line of action of the impact vector, and a 40 f/s vertical impact with a triangular pulse shape having a peak of 31 G and a duration of 0.081 s, with the seat pitched downward 30° and rolled 10° to one side. It was estimated that the seat would be required to stroke approximately 7 inches in order to limit spinal loading to acceptable levels during the vertical test. Simula, Inc., used the SOM-LA computer model (Laananen, various citations) to estimate seat performance requirements in tests with vertical impact velocity components of 25, 28, 31 and 34 f/s. They calculated that the seat would stroke between 2.6 and 8 inches, depending on the velocity and the weight of the occupant, and that the resultant lumbar spine axial load would be between 1990 and 2120 pounds.

The working group had anticipated that their recommendations would result in a seat with energy absorption in the vertical direction. One of the major constraints on such seats is the space available under the seat which would allow the seat to stroke downward while absorbing energy. Structural design of low wing airplanes often results in seats which are located over the wing spar. Goals of aerodynamic efficiency (low aerodynamic drag) tend to reduce the fuselage cross section, and thus limit the amount of space under the seats. This is also a problem in the aft section of the fuselage, where the fuselage tapers inward. The GAMA representatives estimated that three inches of stroking distance (in addition to the space required for vertical adjustment of the seat and the seat adjustment mechanisms) could be provided under the first row of seats. This was judged to be the maximum that could be assured in all aircraft designs and thus limited the vertical component of test deceleration. Moreover, since seats behind the first row may have even less under-seat space for energy absorption, it was decided that a reduction test severity would be necessary for practical tests of those seats.

Working under these constraints, the GAMA presented a detailed proposal to the working group. This proposal attempted to reduce the cost of dynamic testing by combining the goals of the two tests recommended in the Crash Survival Design Guide into a single test. This test would have provided a triangular impact pulse providing a 31 f/s velocity change and a duration of 0.10 s, with the seat oriented at 45° pitch (such that the 50th percentile male anthropomorphic dummy in the test seat would tend to move down and forward) and 10° yaw with the impact vector. Pass or fail criteria would include a 1750 pound limit in the tension force in the shoulder harness and a 1500 pound limit in the compression force in the lumbar column of the dummy. (These limits had been suggested by CAMI in earlier meetings (Chandler, 1985)). The proposal also suggested that the conditions be reduced for seat and restraint systems located behind the first row, since the crash test data indicated that the crash environment was expected to be less severe in those locations, and also recommended increased static test loads.

The effects of this proposal were discussed in the December meeting of the working group. A NASA-LaRC study indicated that the proposed combined test conditions would only require about 2 inches of seat stroke, that a 30° pitch would more realistically evaluate vertical impact, and that a separate longitudinal test should be done to evaluate seat strength and occupant retention. For the vertical test, NASA-LaRC suggested a 22 G impact with a symmetrical triangular pulse shape having a velocity of 36 f/s, with the seat pitched downward 30° and yawed 10°. The 23 G, 50 f/s longitudinal test was again suggested. The Simula study suggested that a vertical test having a triangular pulse shape with 17.4 peak G and a velocity change of 28 f/s, with the seat pitched down 30° and rolled 10° with regard to the impact vector would require a seat stroke of about 2.9 inches, and suggested that an additional 40 f/s longitudinal test with a 20 G plateau, with the seat yawed 10° with regard to the impact vector and occupied by a 95th percentile dummy also be accomplished. These tests were regarded as minimum tests, and should be accompanied by increased static load tests of the seat structure. For optimum dynamic test conditions, a 22.2 G, 36 f/s vertical impact test and 25 G, 50 f/s longitudinal impact test were recommended. Their study indicated that this vertical test would require 6.8 inches of seat stroke distance. It was suggested that the impact velocity should be maintained and the peak deceleration could be reduced in tests of seats behind the first row, but noted that crashes with the aircraft flat or nose up produced more severe decelerations in the aft cabin. CAMI reviewed their dynamic test data and found that the single test would generate floor reaction forces only equivalent to a 6.6 G static load in the forward direction. CAMI concluded that the test was insufficient to demonstrate performance of either seat structure or occupant restraint in the forward direction, and suggested two tests; a vertical test with the seat pitched downward 30° and rolled 10° and having a peak deceleration rising from 0 to 25 G in 0.05 s with a velocity change of 44 f/s, and a longitudinal test with the seat yawed 15° with respect to the impact vector and having a deceleration rising from 0 20 G in 0.05 s with a velocity change of 44 f/s. Both tests were to be done with the seat deformed, prior to the test, by warping the floor. One floor track was to be pitched 10°, and the other was to be rolled 10° to provide the required seat deformation. It was estimated that the seat would stroke approximately 4 inches in the vertical test.

The working group concluded that the single test could produce a useful evaluation of the normal direction energy absorbing characteristics of a seat/restraint system, but could not adequately demonstrate the seat strength or occupant protection in the longitudinal direction. After discussion, a second proposal was developed. This new proposal recommended two dynamic tests, one to evaluate the performance of the seat and restraint system in the normal (vertical) direction (Test 1), and a second to evaluate performance in the longitudinal direction (Test 2). Both tests were to be accomplished with 50th percentile male anthropomorphic dummies as occupants of the seat/restraint system. The vertical test was to be performed with the seat pitched forward (nose down) so that the floor would make a 60° angle with the impact vector. The impact pulse was to be triangular in shape, with a duration of 0.1 s, and provide a velocity change of 31 f/s (parameters consistent with a peak deceleration of 19 G). The second test, also having a triangular pulse shape, was primarily a test in the longitudinal direction, with a lateral component introduced by placing the seat system in a 10° yaw orientation. This test was also to have a duration of 0.1 s, but was to provide a velocity change of 42 f/s (factors consistent with a peak deceleration of 26 G). For both tests, it was recommended that pass/fail criteria include no seat or restraint system failure, no submarining under the seat belt or roll out of the upper torso restraint, a 1750 pound limitation on the force generated in the belt of a single diagonal upper torso restraint system, and a 1500 pound limitation on the compression force between the pelvis and lumbar column of a specified standard 50th percentile anthropomorphic dummy. All tests were to be conducted with floor track as used in the aircraft for connecting the seat to the test fixture. Reduced decelerations (80%) were suggested for seats aft of the front seats. In addition, it was recommended that static tests, with forces equivalent to those generated by a 215 pound occupant (95th percentile male), should be used to demonstrate seat and restraint system performance throughout the aircraft's entire design performance envelope. It was also recommended that the FAA develop advisory material to define acceptable methods and criteria for "floor warping" in the dynamic tests, for secondary impact of the occupant with the interior of the airplane, and for acceptable variations in the shape of the impact pulse.

It was agreed at the December meeting that the CAMI would complete dynamic tests of small airplane seats in accordance with these recommendations, and report the results by the February, 1984 meeting of the working group. Twenty four tests were conducted in this program (Chandler, 1985). Six manufacturers selected two seat designs and provided two specimens of each seat for the tests. One specimen was tested in each of the proposed test configurations. Even though the floor reaction forces measured in the combined vertical and forward loading condition of the first test were relatively low, two seats broke in the tests. Only three seats limited the compression force measured between the pelvis and lumbar column of the dummy to the recommended 1500 pound limit. Problems noted in these tests included the failure of fabric seat pans and the highly elastic response characteristic for most seats. The complex seat adjustment mechanisms provided on crew seats and the elastic nature of the seat pans and seat cushions contributed to this response. The elastic response amplified the impact deceleration as it was transmitted to the occupant. As a result, high forces were measured at the base of the lumbar spinal column in the dummy. Only three seat models did not break or separate from the floor tracks during the longitudinal test. (This result was not unexpected, since most seats were designed to withstand only the traditional "9 G static load" condition.) Many of these problems were associated with joints between structural members, fittings, or the strength of the floor track which was used to attach the seat to the aircraft. Other problems were associated with the restraint system, which released or broke during the test. Premature release of the restraint system was attributed to the misalignment of the latch plate relative to the buckle fitting caused by the pull of the shoulder belt(s).[Note 10]

The results of these tests were presented to the GASP working group in February, 1984. Although the tests created conditions which were more severe than the traditional static load design criteria, manufacturers appeared to have the practical capability for designing and manufacturing seats which could pass the tests. The concept of inducing seat deformation through a "floor warpage" requirement was one of the several additions which were addressed. The need for seat deformation was based on the findings in crash investigations that seats made of strong but unyielding material were found to be broken, or had broken the fittings, the floor track or the fasteners which attached them to the aircraft. It was believed that the forces would be reduced and the seat would stay attached to the floor track if the seat would yield rather than remain rigid. Tests at CAMI confirmed these observations, showing that many rigid seat designs would either break or would break their floor attachment fittings when subjected to the floor deformation procedure suggested by the Army Crash Survival Design Guide (CSDG) (Chandler, 1985). Against the requirement for floor deformation were the arguments that there were no data available which could be called upon to define the proper amount of floor deformation, and that the procedure specified in the CSDG in which one floor track is pitched 10° and the other floor track was rolled 10°, was excessive for small airplanes. A compromise position was finally agreed upon. This called for one floor track to be pitched 10° relative to the other floor track in both tests, but no roll deformation of either floor track was to be required. In reaching this compromise, it was assumed that the (strengthened) rail-type floor track typically used in small airplanes would act as a release mechanism for roll deformation, either bending the web of the rail or allowing the floor track fitting on the seat to roll about the head of the rail.

The components used to attach the seat to the airframe were considered to be a part of the equipment evaluated in the dynamic tests. This would include floor track or attachment fittings which were representative of those used in the aircraft. This was done to provide some minimal assurance that these important components would withstand the stresses generated by the seat and restraint system during the tests. An alternate approach, considered desirable but not included as a requirement, would be to measure the forces and moments generated at each attach point, and then demonstrate through supplementary tests that the components and underlying structure could withstand those forces and moments.[Note 11]

The limitations of spinal column load, shoulder belt load, submarining, and upper torso roll out of the restraint system were intended to limit injury to the occupant. Techniques for injury assessment through dynamic testing have been extensively studied by researchers concerned with the reduction of crash injuries in automobiles. Early in that work, it was found that different anthropomorphic dummies could have widely varying response to the crash environment. It was necessary to standardize on a specific dummy design which would be used in all tests. The automobile industry has standardized several anthropomorphic dummies to use in their tests. While a wide variety of dummies have been used for evaluating ejection seat performance, these devices have not been standardized, and are generally unsuitable for investigating fixed seat performance because of their non-anthropomorphic construction or their cost. For these reasons, a seated form anthropomorphic dummy originally developed for automobile research was adapted to the tests of aircraft seat and restraint systems. This dummy is standardized in the U.S. Code of Federal Regulations, Title 49, Part 572, Subpart B. It is the 50th percentile male dummy commonly known as the "Hybrid II." These dummies are generally available at most crash test facilities.[Note 12]

The Dynamic Response Index (DRI), used to infer the likelihood of spinal injury during seat ejection in combat aircraft (Brinkley, 1968), was first considered as a method for estimating spinal injury for these recommendations. The DRI represents the maximum response of a single degree of freedom, damped, spring mass oscillator with a natural frequency of about 8 Hz, forced into oscillation by the acceleration of the seat. However, the DRI could not be directly applied to tests of small airplane seats because of the requirement that an acceleration representative of the entire seat be used for the computation of DRI. The light weight and flexible construction of most small airplane seats produces a great variation in seat acceleration data, depending on the site of the measurement. Thus, no simple measurement of acceleration on the seat can be considered representative of the entire seat. Although some authors have calculated a "DRI" from accelerations measured in the dummy's pelvis, there is, as yet, no validated technique for relating this "Pelvic DRI" to spinal injury. Thus it became necessary to correlate the DRI with some other simple measurement. An earlier test program at CAMI had made use of a load cell inserted at the base of the lumbar spinal column of the dummy for a direct measure of lumbar compression (Coltman, 1983). This technique was developed and used in a series of tests of a seat with a fairly rigid seat bucket. A valid DRI could be calculated from those tests, and this was compared with the direct measurement of lumbar column compression in the dummy (Chandler, 1985). This comparison indicated that a pelvic/lumbar column compression load of 1500 pounds would correspond to a DRI of about 19, which would indicate a 9% probability of detectable spinal injury in ejection seats. While the frequency and severity of injury in small airplane crashes is likely to be somewhat greater because of the increased age of the occupants and less effective restraint systems, the 1500 pound limit on compressive lumbar force in the dummy was still considered acceptable. It was also observed in the comparison tests that the lumbar force measurement decreased in impacts where the seat was rear facing (so the occupant was forced down and to the rear in the impact), but there was no corresponding decrease in either the DRI or acceleration measured in the dummy's pelvis. The lower lumbar load in rear facing seats is consistent with the findings of accident investigation, which indicates reduced spinal injury for occupants seated in rear facing seats when compared to those facing forward. The sensitivity of the lumbar load measurement to these conditions, and to possible spinal compression forces from shoulder belts anchored below the shoulders, provides advantages which are not present in injury criteria based solely on acceleration measurements.

The criteria for allowable shoulder belt force was derived from research on automobile crash injury. The belt load at the upper end of the shoulder belt was found to be the most sensitive parameter relating to chest injury when comparing injuries observed in crashes with measurements made on anthropomorphic dummies in similar controlled tests (Patrick, 1974). Data from investigations of actual crashes in which the occupants were restrained by a lap-belt and a single diagonal shoulder belt with force indicators at the upper end provided data to estimate the relationship of strap force and injuries (Foret-Bruno, 1978). Analysis of these data led to the selection of the criterion limiting the force in a single strap upper torso restraint to 1750 pounds. This represents a force which could be expected to produce serious, but not life threatening, chest injuries in an average 37 year old male occupant. The limitation of 2000 pounds total force in an upper torso restraint system with dual shoulder straps was empirically selected, but is consistent with measurements made on military restraints (Singley, 1981).

The use of the Head Injury Criterion (HIC) is also a well established practice in the automobile industry (e.g. SAE J885, April 1980). The HIC was chosen for the small airplane seat tests because of its long history of use and acceptance. Although there are numerous other techniques for modeling head injury, no single technique has yet successfully challenged the HIC. However, the HIC is significant only if head impact does occur. Head motion without impact can also generate accelerations which will yield high values of the HIC, but they are of no significance for inferring injury. To circumvent this problem, the GASP working group chose to limit HIC computations to acceleration duration intervals of 0.05 seconds or less. Supplementary tests may be needed for measuring the HIC which could result from head impact with the interior of the cabin because the interior may not be defined at the time the seats are tested, or may undergo several changes during the life of the aircraft, or because the seats may be used in many aircraft having different interiors. A supplementary test in which a weighted head form is used to impact the interior was considered acceptable (e.g., SAE J921, 1971). The movement of the dummy's head in the seat tests would be used to establish the impact point, impact velocity, and impact direction for the supplementary tests.

The prohibition of submarining reflects the well established concern for limiting spinal injury and internal abdominal injury. These injuries have been of concern since belt type restraint systems were first used (e.g. DeHaven, 1947). Submarining can usually be detected by the rapid movement of the lap belt over the pelvis as sometimes seen in high speed film coverage of the tests. It can also be detected by special "submarining indicators" located on the anterior iliac spines of the dummy's pelvis, or indicated by marks in special "crushable" foam inserted into the dummy's abdominal cavity. The criteria prohibiting the upper torso from "rolling out" of restraint is of particular concern with restraint systems having a single diagonal belt for upper torso restraint. This action may occur in a crash if the effective line of action of the inertial response of the upper torso passes above the diagonal belt (Carr, 1975). Several early shoulder belt installations in small airplanes simply attached a single shoulder belt to the centrally located lap belt buckle. Most of the mass of the occupant's upper torso is above the shoulder belt in such installations, so that the upper torso is likely to roll over the shoulder belt, with resultant head and spinal column injuries.

The proposal was evaluated by the NTSB and Simula, Inc. in view of their recent studies of aircraft crashes. The NTSB recognized that the test for energy management in the vertical direction was minimal and should be increased if additional stroking distance was available under the seat. In general, they concluded that the proposal would offer substantial protection in severe but survivable crashes. They estimated that fatal accidents would decrease by 20 percent, serious injuries would decrease by 34 percent, and the extent of serious injuries would be reduced by 88 percent in survivable accidents of aircraft that incorporated the proposed criteria. The position of Simula Inc. was that the proposed criteria would represent a significant advance in crashworthiness for small airplanes, and would not require sophisticated technology for implementation. They restated their support for a floor deformation requirement, and recommended that the time duration of the pulse for the first (vertical) test be limited to 0.075 seconds, without change of the 31 f/s impact velocity, in order to improve the minimal requirement for seat energy absorption in the vertical direction.

The GASP proposal was formally submitted to the FAA on May 2, 1984 (Olcott, 1984). It was supported by the General Aviation Manufacturers Association at the Review Conference for the Small Airplane Airworthiness Review Program held in St. Louis Missouri, in October, 1984. The GASP proposal, along with several other proposed changes in rules pertaining to general aviation airplanes, was included by the FAA in a Notice of Proposed Rulemaking (NPRM) issued in December, 1986. The only significant change of the GASP proposal made in the NPRM was the elimination of the floor warping requirement for the vertical test. This change was based on testing done at CAMI on prototype seats intended to meet the requirements of the GASP proposal. These seats used the deformation of seat legs to meet the energy absorbing requirements. It was found that in tests where the floor was warped, one pair of legs was more highly loaded than the other, and the deformation characteristics of the highly loaded legs controlled the energy absorbing performance of the seat. However, when the floor was not warped, both pair of legs were almost equally loaded, and the seat would not deform. This resulted in higher loads on the occupant. There was no simple technique for designing these seats to provide the same energy absorption with and without floor deformation.[Note 13] It was further reasoned that the longitudinal test provided the best test of the ability of the seat to remain attached to the airframe during a crash, and that floor warpage in that test would achieve the primary goal of demonstrating adequate seat retention. As a consequence, floor warping was retained as a requirement for the longitudinal test, but dropped from the requirements for the vertical test.

After receiving and considering public comments regarding the NPRM, the FAA issued the final rule on August 15, 1988. The only significant change from the NPRM was the addition of roll deformation as part of the floor warp required for performing Test 2. This was done on the basis of public comment, and with knowledge of testing done at CAMI which indicated that the assumption that the floor track would provide adequate roll relief was not valid. The dynamic test requirements of this rule are shown in Table 19.

While the preceding discussion has addressed the requirements developed for occupant crash protection in small airplanes with less than 10 occupants, the General Aviation Safety Panel also served as a forum for developing occupant crash protection requirements for helicopters. Data from the helicopter crash investigation study by Simula (Coltman, 1985) was supplemented by crashworthiness studies and design developments by Bell Helicopter Textron (e.g. Fox, 1983, 1986, 1989) and data from the Crashworthiness Project Group of the Rotorcraft Airworthiness Requirements Committee of the Aerospace Industries Association for establishing the helicopter requirements. A concern that the "built in" helicopter seat concept might not be adaptable to energy absorbing requirements was resolved by a program which had been initiated by the U. S. Army Aeromedical Research Laboratory with Bell Helicopter Textron for retrofiting a crashworthy seat into the OH-58 helicopter. (The OH-58 is similar to the civil Jet Ranger helicopter.) The crew seats in the OH-58 helicopter were integrated into the fuselage structure. The fixed seat pan of the "built in" seat was replaced with a seat pan which absorbed energy as it pivoted around a hinge at the forward edge of the seat. Between 5 and 8.25 inches of stoke distance could be achieved in this manner to offer protection against crashes with vertical velocity changes between 30 and 35 f/s. The seat belt installation was modified so that the seat belt would follow the seat pan downward as it stroked to avoid submarining of the occupant. The concept proved successful in a variety of dynamic tests conducted at CAMI in 1988. The dynamic test requirements established by the FAA for helicopters are also shown in Table 19.

The question of fuel systems crashwortiness for small airplanes was investigated by a second General Aviation Safety Panel (GASP II) (Madayag, 1989). A review of 667 crashes of general aviation aircraft with serious or fatal injuries, in 1983, formed the basis for this study. Only 250 of those crash reports had sufficient data for evaluating crashworthiness. Information on fuel spillage was available for 121 of the 150 survivable crashes. Of those crashes,

a. Fuel spilled in 96 crashes.
b. Fuel tanks ruptured in 78 crashes.
c. Fuel was spilled from one or more fuel lines in 48 crashes.
d. Fuel was spilled from one or more fittings in 22 crashes.
e. Post crash fire occurred in 27 crashes.
f. Ten fatalities occurred in five crashes with post crash fires.

These data indicate that about four to five percent of the severe but survivable crashes involved fatalities due to fire. Fuel was spilled from the fuel tanks in all five crashes which involved fatalities. Fuel spillage from lines or fittings was noted in two of those crashes.

Since fuel spilled from fuel tanks was a common factor in all fire fatalities, the option of using crash resistant bladders in fuel tanks located in the wings was evaluated by the GASP II committee (Soltis, 1988). They concluded that the installation of crash resistant bladders in small general aviation airplanes would reduce the volume of fuel carried by the aircraft by 13 to 14 percent for most aircraft, with a corresponding decrease in range. Because the relatively low risk of fatalities due to post crash fires, and because of concerns that a 13 to 14 percent decrease in range could increase the risk of crashing because of more frequent landings and takeoffs or an increased risk of fuel exhaustion, it was concluded that crash resistant bladders in wing fuel tanks should not be a mandatory requirement for all small airplanes.

The final conclusions of the panel were:

a. Fuel lines should be designed so that no more than 8 ounces of fuel spillage per fitting would occur if lines or fittings were to break in the wing/fuselage juncture, the firewall/engine-mount juncture, the juncture between tip tanks and wings, and the dry bay area behind an engine if used to carry fuel.

b. Any fuel tank located in an engine nacelle, between the engine and an occupied area, or any (non-wing tip) tank external to the wing should comply with Mil-T-27422B, Crash Resistant Aircraft Fuel Tank, with the following exceptions:

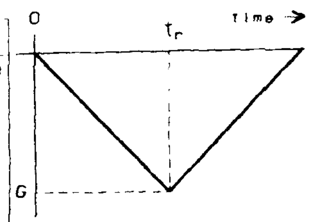
   Constant tear rate: The minimum energy for complete separation shall be 200 foot pounds.

   Impact penetration: The drop height of the five pound chisel shall be 8 feet.

   Impact tear: The drop height of the five pound chisel shall be 8 feet and the average tear shall not exceed 1 inch.

Table 19. DYNAMIC TEST REQUIREMENTS FOR U.S. CIVIL AIRCRAFT

Category	Test Parameter	Test 1	Test 2	Criteria for pass or fail
SMALL AIRPLANES, 9 or fewer passengers. U.S. 14 CFR[1] Part 23, § 23.562 (Amendment 23-36) First row of seats				HIC must be ≤ 1000 during head impact.[2]
				The ATD[3] must be restrained.
	Minimum velocity change	31.0 f/s	42.0 f/s	Seat may deform if intended by design.
	Maximum rise time	0.05 s	0.05 s	Attachment between seat/restraint system and test fixture must be maintained.
	Minimum deceleration	19.0 g	26.0 g	
	Floor track misalignment, Pitch / Roll	0°/0°	10°/10°	Shoulder belt(s) must remain on the ATD's shoulder(s).
Seats behind first row	Minimum velocity change	31.0 f/s	42.0 f/s	Safety belt must remain on the ATD's pelvis.
	Maximum rise time	0.06 s	0.06 s	Individual shoulder strap load must be ≤ 1750 pounds, with total (dual) shoulder strap loads ≤ 2000 pounds.
	Minimum deceleration	15.0 g	21.0 g	
	Floor track misalignment, Pitch / Roll	0°/0°	10°/10°	The compression force between the pelvis and lumbar spine of the ATD must be ≤ 1500 pounds.
TRANSPORT AIRPLANES U.S. 14 CFR Part 25, § 25.562 (Amendment 25-64)	Minimum Velocity Change	35.0 f/s	44.0 f/s	As for small airplanes, plus:
	Maximum Rise Time	0.08 s	0.09 s	If leg impact occurs, femur force must be ≤ 2250 pounds.
	Minimum Deceleration	14.0 g	16.0 g	
	Floor track misalignment, Pitch / Roll	0°/0°	10°/10°	Seat deformation must not impede rapid evacuation of the airplane occupants.
NORMAL CATEGORY ROTORCRAFT U.S. 14 CFR Part 27, § 27.562 (Amendment 27-25)	Minimum Velocity Change	30.0 f/s	42.0 f/s	As for small airplanes, except:
	Maximum Rise Time	0.031 s	0.071 s	The seating device may experience separation if part of design.
TRANSPORT CATEGORY ROTORCRAFT U.S. 14 CFR Part 29, § 29.562 (Amendment 29-29)	Minimum Deceleration	30.0 g	18.4 g	
	Floor track misalignment Pitch / Roll	10°/10°	10°/10°	The shoulder harness must remain on or in the vicinity of the ATD's shoulder.

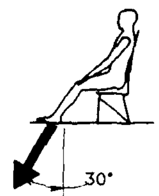


Test Pulse Simulating Aircraft Floor Deceleration-Time History:

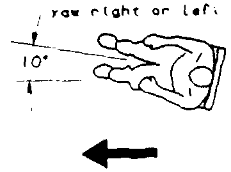
t_r = rise time

V_i = Impact Velocity

TEST 1:



TEST 2:



Notes: 1. U.S. 14 CFR refers to the United States Code of Federal Regulations; Title 14; *Aeronautics and Space*, which contains regulations set forth by the U.S. Federal Aviation Administration.

2. "HIC" refers to the "Head Injury Criterion," a computation which uses acceleration measurements made in the head of the anthropomorphic dummy to infer head injury.

2. ATD means a 50th percentile anthropomorphic test device (dummy) in accordance with U.S. 49 CFR 572, Subpart B. This is the "Hybrid II" seated form dummy developed for automobile impact testing, and adapted for the aircraft seat tests.

> Crash Impact Phase I: Delete
>
> Crash Impact Test of Full-Size Production Test Cell: The cell shall be filled with water to 80 percent of normal capacity, and the air removed. The cell shall be placed upon a platform and dropped from a height of 50 feet, without leakage after impact.

These recommendations are being proposed for rulemaking by the FAA at the time of this writing.

Several other actions have been taken by the FAA in response to the GASP recommendations. A new regulation requires that shoulder harnesses be installed for all passengers in small airplanes manufactured after December 12, 1986. Advisory Circulars have been issued for the following topics:

a. Injury Criteria for Human Exposure to Impact (AC 21-22)
b. Static Strength Substantiation of Attachment Points for Occupant Restraint System Installations (AC 23-4)
c. Dynamic Testing of Part 23 Airplane Seat/Restraint Systems and Occupant Protection (AC 23.562-1)

Advisory Circulars for Shoulder Harness - Safety Belt Installations and for Analytical Methods are being prepared.

<u>The Cessna Caravan 1 Crew Seat</u>. Coincident with the work by the General Aviation Safety Panel on improved occupant crash protection, Cessna Aircraft Company proceeded with a program for developing a crew seat for the new Caravan 1 airplane (Rathgeber, 1985). The Caravan 1 is a large single engine turboprop airplane designed for diverse private, commercial and utility applications. Since the cabin is large to allow the desired cargo and passenger hauling capabilities, there was sufficient space to accommodate energy absorbing seats for the crew. The Caravan 1 Crew Seat Project began in early 1983, and continued into 1984. During that time, many seat/restraint system concepts were evaluated, and several prototype designs were dynamically tested by the FAA Civil Aeromedical Institute. When the project began, the GASP had not yet agreed on recommendations for test criteria. The results of the project were provided to the GASP, and assisted in evaluating the practicality of the various approaches being considered by the panel. As the GASP proposed new criteria, the seat design and dynamic testing program was adjusted to meet the new criteria. In effect, the Caravan 1 Crew Seat Project became a demonstration project for the GASP recommendations.

The first seat designed in this program was made of steel tubing with the front and rear legs formed into the shape of a "C" to provide energy absorption under vertical loads. A five-point restraint system was used, with the dual shoulder belts attached to the test fixture in a manner which simulated overhead aircraft structure. The seat belts and seat belt tie down strap were attached to the seat frame. Four 47 f/s dynamic tests were conducted with this seat mounted as if the floor was pitched up 34 degrees relative to the horizontal impact vector. Test data showed that the seat was adequate for 8.8 G impacts. However, as the test deceleration was increased, pelvic deceleration, lumbar forces, and restraint system loads increased, and submarining was observed. Tests exceeding 15.8 G produced excessive dummy accelerations and loads, high restraint system loads, and predominant submarining.

The second seat designed in this program used a seat having a parallelogram four-bar linkage seat leg configuration, with an energy absorber along the long diagonal of the parallelogram. This seat also used a five point restraint system, fitted as before. It was found difficult to balance the stroke and force level of the constant force energy absorber to obtain efficient stroking with the four bar linkage. It was also observed that the four bar linkage system would move the occupant forward so that head contact with the instrument panel could be made more severe.

The seat design used in the first series of tests was modified by replacing the neoprene covered nylon seat pan with a pan made of sheet aluminum. The restraint system was modified by providing special "rip-out stitching" in the common strap of the shoulder belts. This stitching was designed to tear progressively under load, provide energy absorption, and allow the shoulder belts to elongate so that the seat could stroke downward. The test results indicated that the tendency of the dummy occupant to submarine was reduced by these modifications. The four-bar linkage seat system was modified in a similar manner, but tests on this seat were inconclusive because of erratic performance of the seat energy absorber.

The four-linkage seat was modified by replacing the forward link (which formed the front leg of the seat) with a "C" shaped steel tube with ends fixed to top (seat pan) and bottom (floor track attachment fitting spreader) links. The "C" shaped tube was to act as the energy absorber. A five point restraint system made of polyester webbing was used for these tests. This design showed better control of dummy motion at lower impact levels, but broke at higher decelerations. Since the restraint system was attached to overhead structure through the shoulder belts and to the front edge of the seat pan through the lap belt tie down strap, the seat could not stroke downward. Instead, the downward and forward forces were reacted at the forward edge of the seat pan, where the lap belt tie down strap was attached. The seat and restraint were not designed to carry high loads in this manner, and broke. The seat was mounted at a 30 degree or 60 degree pitch angle for these tests. Compressing force in the dummy lumbar spine was approximately 1100 pounds, in 30 G, 50 f/s tests, but submarining occurred after the lap belt tie down strap broke. The floor was warped (using the 10 degree pitch, 10 degree roll concept described in the U.S. Army Crash Survival Design Guide). The seat accommodated this floor deformation without structural failure.

After these tests, the seat was redesigned to incorporate a four point restraint system attached entirely to the seat. This restraint system used two shoulder belts, attached to the center of the top of the seat back through an inertial reel. The lower ends of the belts were attached to the seat pan at the seat belt attachment points. A conventional seat belt was also used. An aluminum seat pan was used to limit elastic deformation. These changes were made to better restrain the occupant, and reduce submarining. The four bar linkage arrangement with "C" shaped front links was retained to act as the seat legs. Several minor design deficiencies were identified during the dynamic tests of this seat, and these were corrected. The final tests of this seat design were done in accordance with the recommendations of the GASP. Data collected during these tests indicated that the seat would meet all the criteria for those tests. Altogether, twenty-three dynamic tests were accomplished in this development effort.

Restraint System Requirement. One of the recommendations of the General Aviation Safety Panel was that the Federal Aviation Administration issue revised specifications for restraint systems with shoulder harnesses which would be consistent with the minimum dynamic performance standards being developed by the GASP. To assist in this effort, the FAA requested the Society of Automotive Engineers to develop an Aerospace Standard which could serve as a basis for a new FAA standard. To do this work, the SAE established an Ad Hoc Committee on Upper Torso Restraint Systems.[Note 14]

The first meeting of the committee was held at the FAA Civil Aeromedical Institute in February, 1984.[Note 15] During this meeting, it was observed that no major revision had been made to the (then) current standard for aircraft restraint systems since it was issued in 1948. Since that time, numerous standards and improved techniques for "belt-type" restraint systems had been independently developed by various segments of the automobile and aviation communities. It was decided that the committee should evaluate these new approaches and attempt to consolidate the more significant items into a single document. This document would not supersede the dynamic test requirements being developed by the General Aviation Safety Panel, but would describe supplementary procedures and requirements deemed essential for good restraint system performance. Since the document was intended to describe minimum requirements, the committee decided not to include performance characteristics for restraint system components which were not commonly found in small aircraft. Consequently, new requirements for components such as powered webbing retractors, "window shade" devices for comfort relief of shoulder belt tension, and emergency locks which act directly on the restraint webbing were not to be included in this initial document. In the next four formal meetings, the committee collected and examined standards and procedures developed by the U.S. and international automobile community, the various military services, or used by the restraint systems industry for internal product or quality control.

The first draft of the proposed Aerospace Standard was completed in May, 1984, and submitted to committee members and other interested parties for comments and approval. After several iterations of the review process, all comments were considered and resolved. The final draft was submitted to the SAE in September, 1985, and issued as SAE Aerospace Standard 8043, Torso Restraint Systems, in March, 1986. The new Standard provides test procedures and performance requirements for both individual components and the assembled restraint system. Criteria are given for component strength, elongation, dimensions, buckle release force, webbing adjustment force, tilt-lock adjustor performance, limits on slippage through adjustment devices, reliability, emergency locking retractors, and resistance to degradation due to abrasion, corrosion, solvents, light and life cycle. A system assembly test requires that the pelvic restraint (seat belt, safety belt or lap belt) be capable of resisting a total force of at least 26.6 kN (6000 pounds), and that the combination of pelvic restraint and shoulder belt restraint be capable of resisting a total force of at least 33.3 kN (7500 pounds). The FAA adopted the Standard as FAA Technical Standard Order C114, Torso Restraint Systems, in March, 1987.

Seat/Restraint Systems for Transport Airplanes - CAMI Seat Testing. In February, 1979, the FAA Civil Aeromedical Institute initiated a program for evaluating the performance of passenger seat/restraint systems used on civil transport airplanes (Chandler, 1985). The primary purpose of the study was to compare the occupant protection and failure modes of several different seat designs when subjected to various dynamic testing conditions and to simple static tests. Secondary goals were to evaluate the effectiveness of the "brace for impact" passenger position, the problem of seat/floor deformation as a cause of seat or floor track failure, and to begin development of a data base which could be used for validating computer modeling of the transport airplane seat, restraint, and occupant system. Loads (forces) transmitted between a segment of floor track under each leg of the seat and the test fixture were recorded in all tests.

Initially, ten test conditions were planned for this program:

1. Static tests with forward loading by body blocks.
2. Static tests with pre-deformed floor.
3. Dynamic tests with forward ($-G_x$) loading.
4. Dynamic tests with forward loading and loads from passengers (dummies) seated behind the test seat.

5. Dynamic tests with forward loading and floor deformed.
6. Dynamic tests with forward loading, floor deformed, and passengers seated behind the test seat.
7. Static tests, forward loading with seat yawed 30 degrees.
8. Dynamic tests, forward loading with seat yawed 30 degrees,
9. Dynamic tests, forward loading with seat yawed 30 degrees and floor deformed.
10. Dynamic tests with the seat oriented to distribute a combined load in the forward, downward and sideward direction in the ratio 9:4.5:1.5. This was the same ratio as specified by FAA regulations for independently applied static loads.

Test seats were purchased commercially, or were obtained from sources within the FAA. All seats were in used but serviceable condition. Two and three passenger seat assemblies, each with four seat legs, and of designs characteristic of seats in use prior to the introduction of so-called "lightweight high density" passenger seats were made available for the program. The seats incorporated a variety of design and construction details, and one design incorporated an energy absorber between the seat and the seat frame (Teco, undated).

It was understood, from theoretical analysis and actual testing, that variations in dynamic test deceleration pulse shape can create significant variations in the response of the seat. It was not possible to investigate the effects of these variations in the limited program which was planned. However, studies of a simple mass-spring system had suggested a technique for relating the response of the system under transient dynamic loads to the response of the system under static (constant acceleration) loads (Kornhauser, 1954, 1964).[Note 16] Tests based on that technique had been suggested as a means of developing dynamic test requirements which would be consistent with static design requirements (Voyls, 1969). Following these concepts and assuming that the test seats would all have about the same natural frequency, an impact pulse shape which was trapezoidal in form, with a consistent rise time to maximum deceleration and with a duration sufficiently long to encompass the maximum response of the seat, restraint, and occupant system was selected for the dynamic tests. With the constant rise time, the average deceleration could be increased by increasing the plateau of the trapezoidal pulse without changing the maximum response due to pulse shape variations. The average deceleration could then be related to an equivalent static load. From a practical viewpoint, it is necessary to increase the deceleration level in discrete increments in a series of dynamic tests, rather than gradually as would be done in a static load test. Thus, the deceleration level of a dynamic test which resulted in failure of a system would be the upper limit rather than the exact equivalent of a static test required to cause similar failure. For this test program, it was decided to apply the dynamic test loads at 3 G increments, with a consistent impact velocity of about 50 f/s. This method provided for a systematic evaluation of seat performance without the need for replicating any particular aircraft crash.

The test plan initially anticipated that seats which did not fail in the low deceleration tests could be re-tested at greater decelerations. However, early in the program it was decided that this approach would risk testing a seat with undetected damage, and could cause incorrect test results. It was then necessary to reduce the number of tests to agree with the number of seats available. Test conditions 6 and 7 were eliminated, and the number of tests under condition 4 were reduced. All dynamic tests were made with 50th percentile anthropomorphic dummies in each passenger seat. In tests with two rows of seats, 5th, 50th and 95th percentile dummies were seated in the second row.

Comparison of the static and dynamic tests (Conditions 1 and 3) indicated significantly different load applications. The static loads were applied through standard body blocks which were held in the seats by passenger seat belts. The forward load was applied to the body block at a height of 10.5 inches above the top of the seat cushion. This load application caused the block to rotate, and apply high forces to the front edge of the seat. This would cause the front edge of the seat pan to collapse on some seats. The effective line of action of the forward pull force would then drop towards the level of the seat belt attachment points. If the seat pan did not collapse, the effective line of action would move from about 18 inches to about 12 inches above the seat belt attachment points as the seat cushion compressed and the body block rotated.[Note 17] This was distinctly different from the results of the dynamic tests, where the effective line of action of the inertial loads from the seat and dummies (as calculated from the vertical and horizontal forces measured under each seat leg) passed within a radius of about 4 inches from the seat belt attachment points throughout the test. This indicated that the traditional static test method was conservative in the sense that it would produce a greater structural stress than a dynamic test with equivalent forward loading. However, the traditional static test could provide misleading data for some seat designs. For example, consider a seat with legs designed to collapse under forward load in order to limit the forces on the occupant. If such a seat were made so that the front legs collapsed under the action of the rigid body block which produces high vertical loads on the front edge of the seat pan, the forces required to collapse the legs under dynamic conditions might be so great as to injure the occupant.

These results indicated that there could be no functional comparison of the traditional static test results with the dynamic test results.[Note 18] However, analysis of the floor reaction forces measured in the dynamic tests indicated that the magnitude of the vector sum of the floor reaction forces was approximately 1.69 (standard deviation

= 0.25, standard error of estimate = 0.06) times the total weight of the seat and dummies times the deceleration measured on the sled. In other words, under the condition of these tests, the stresses in the structure of the seat and floor averaged 1.69 times that which would have been expected by the basic considerations of "static equivalent" loading.

The deceleration level of tests in which the seats failed is shown in Table 20. No tests were accomplished with sled decelerations greater than 12 G. The floor track failed in eight tests which included either a lateral load component or a deformed floor. One seat design did not provide relief from pitch or roll bending moments at the floor track fitting. This tended to break the floor track or the attachment studs in the floor track fitting when the floor was deformed. Subsequent static tests of the floor track indicated a statistically significant decrease in floor track strength when the floor track was rolled 10° relative to the line of action of the force so that the forces were concentrated along one edge of the track. Seat belts failed in several tests. In the static tests, the failure was associated with the collapse of the seat pan under the body block. When the body block was finally supported by the seat structure, it acted as a lever to break the belts. In the dynamic tests, the occasional seat belt failure occurred at points where the webbing passed over seat belt hardware such as adjusting bars or anchorage fittings.

Table 20. Seat Failures vs. Sled Deceleration, G

Sled deceleration, G	Test Condition				
	3	5*	8	9*	10
6	0	4	5	2	1
9	6	1	3	2	1
12	3	1	n.a	n.a	5
Total tested	9	6	8	4	7

* Three seats failed during the pre-test application of floor deformation, and were not dynamically tested.

The dynamic tests with two rows of seats provided data on the interaction of the dummies with the seat row in front of them. Even though the head impacts were not severe, the "brace for impact" position reduced the severity of head impact even more. In tests where eleven dummies in the second row were not braced, head impact, as measured by the Head Impact Criterion (HIC) ranged from 80 to 863. In tests with 4 dummies braced by flexing forward over the seat belt with the head resting against the forearms on the seat back in front, the HIC ranged from 31 to 260. A HIC of 1000 is generally considered to be critical. It should be noted that all the seats used in this program were provided with seat backs which would "breakover" when forces of 20 to 95 pounds were applied to the seat back at the top. Knee motion was also measured in the tests. In the forward facing dynamic tests, it was found that the dummy's knees would move forward approximately 3.2 inches in the 6 G tests, 4.6 inches in the 9 G tests, and 5.2 inches in the 12 G tests (before seat failure). These measurements indicate that knee contact with the seat in front can occur, and may cause injury as well as introduce unexpected loads on that seat.

The energy absorbing seat provided for this program used a thin, contoured, foam filled thermoplastic shell for the seat pan and back. The shell and the seat legs were attached to an aluminum torque tube which ran under the entire seat assembly. The attachment mechanism between the shell and the torque tube provided a seat recline mechanism as well as an energy absorber which would dissipate energy as the seat rotated forward 62° around the tube. Literature describing the seat indicated that it had been "tested to 30 G's at .05 seconds and 20 G's at .10 seconds". However, in the CAMI test program, the floor track attachment fitting failed in a 6 G test and was redesigned and replaced to continue the program. The rotational motion of the seat bucket allowed the dummy's knees to move forward 9 inches in a 6 G test and 12 inches, prior to seat failure, in a 9 G test. The forward head displacement of dummies in this seat exceeded 42 inches in the 9 G test, compared to a mean value of 34 inches measured in other seats. In addition, it was observed that the rotational motion of the seat bucket in a crash would tend to enclose an occupant between his seat bucket and the seat in front, so that emergency egress could be difficult.

FAA/AIA/ATA Seat Test Program. The next major passenger seat test program at CAMI was undertaken as a joint effort with the Aerospace Industries Association (AIA) and the Air Transport Association (ATA) in anticipation of FAA rulemaking for improved passenger seat performance. This program began in 1984, after the General Aviation Safety Panel completed its recommendations for improved seating and restraint systems for small aircraft. This project provided a means for transport airplane seat manufacturers, airframe manufacturers and airline operators to participate in dynamic testing, define the limits of existing designs, and understand how dynamic testing could be used as a practical technique for improving the performance of seats in transport airplanes. A program (Webster, 1988) was developed to investigate the effects of pulse shape, the interaction of deceleration level and impact velocity, two versus three occupants in triple-seat assemblies, the effects of floor deformation, the effects of impacts with vertical load components, and the effects of multiple row seating. Most tests were performed using one model of seat with design characteristic of seats in use prior to the introduction of so-called "lightweight high de sity" passenger seats. These seats were modified by CAMI as necessary to increase seat strength for the more severe tests. Nine seats which were currently under development by seat manufacturers were included as the program progressed.

Impact tests which generated forward loading on the seats were conducted at peak decelerations between 7 and 12 G's and with impact velocities from 25 to 50 f/s. It was found in tests with the same impact velocity, peak deceleration and onset time (time to peak deceleration), that a trapezoidal shaped impact pulse would generate greater loads in the seat legs than would a triangular shaped pulse. Tests of triple-seat assemblies with only two occupants (in the center and overhang seats) generated 13 percent greater loads in the critically loaded seat leg than did tests with three occupants.[Note 19] In tests with seats yawed 10° from the forward longitudinal impact direction, tests with the overhang seat in the leading position increased the critical front seat leg load, while tests with the overhang seat in the trailing position increased the critical rear seat leg load. In tests with constant velocity, the seat leg loads appeared to be primarily a function of peak deceleration. In tests with consistent peak deceleration, but with increasing impact velocity, the seat leg loads were limited by the plastic deformation of the seat structure. Reinforcement of the seat structure so that it had greater strength, i.e., would accommodate more severe impacts without plastic deformation, greatly increased the loads in the seat legs (and the loads in the floor track and floor).

Tests in which the floor (track) was deformed prior to impact indicated that the test seats could accommodate approximately 6° of elastic deformation. Pre-test floor (track) deformation up to 10° produced no significant change in the maximum seat leg loads measured during the dynamic tests.

Tests with the seat assembly pitched upward 60° with respect to the horizontal impact vector (so the dummy inertia loads would be directed forward and down relative to a longitudinal aircraft axis) indicated amplification of seat leg loads between 8 percent for the older seats and 25 percent for the new seat designs. Compression forces measured at the base of the lumbar spine in the dummy ranged between 500 and 1400 pounds. The newer seats tended to produce greater lumbar spine compression forces. The lumbar spine compression force decreased in the center seat position, but increased in the outer seat position, in 14 G tests as the impact velocity increased from 29 f/s to 40 f/s.

In the multiple row tests, it was found that compression loads measured in the femur of the dummy's legs were greatest with the seats spaced to provide about 3 inches of clearance between the dummy's knees and the seat back. Seat leg loads in the forward seat also appeared to peak at this clearance because of the reaction with the dummy's legs. A Head Injury Criterion (HIC) greater than the threshold injury level of 1000 was measured in only one test.

Measurements of the forces transmitted between the floor track and the seat attachment fittings provided the most useful data obtained in this program. These data allowed designs to be initiated which were based on measured forces rather than empirical estimates of loads and thus provided the seat manufacturers with understanding of the stresses generated in the seat during dynamic tests. Equally important, it provided a basis for establishing a requirement for improved seat performance which would be consistent with the floor strength of the transport airplane. For example, Figure 33 shows the forces measured at the floor track under the forward and rear legs of seats used in dynamic tests where the seat did not break. An allowable seat floor load for the airframe is also shown. The test results, shown with triangular markers, was primarily a function of the deceleration and impact velocity of the tests. Simple statistical analysis of these data provided estimates of floor loading which could be expected under other conditions of deceleration and impact velocity with the same triangular shaped impact pulse. For example, these seats would be expected to generate loads in the floor corresponding to the circular marker in a test with 16 G peak deceleration and a 44 f/s impact velocity. This is well within the boundary shown for allowable floor loads, and provides some margin for designs which differ from those of the test seat, such as reduced spacing between the forward and rear leg fittings which might be required in high density seat systems.

<u>Industry Tests at CAMI</u>. As this test program was being conducted, seat manufacturers began submitting a variety of prototype seats for testing. Although several of the prototype seats failed to complete the tests in the first attempt, the experience gained in these programs, and the data obtained from measurements of forces introduced into the seat structure during the dynamic test enabled successful designs to be developed. Several seat manufacturers soon announced that they were able to supply seats capable of passing a 16 G dynamic test and accommodating floor deformation (e.g., Weber, 1986). The Federal Aviation Administration issued a Notice of Proposed Rulemaking for improved seat safety standards for transport airplane seats (FAA, 1986). Seat manufactures announced they could comply with the proposed requirements, and airframe manufacturers and airline operators began to reference the proposed rule as an additional requirement when purchasing seats. Numerous comments were received in response to the Notice of Proposed Rulemaking by the FAA. Some of these comments indicated that there was confusion, particularly among manufacturers outside the United States, regarding the dynamic test methods or the goals of providing occupant protection to supplement the traditional goals

of seat structural strength. To help resolve these problems, the CAMI program was expanded to provide cooperative testing with transport airplane seat manufacturers from outside of the United States. This expanded program was intended to aid in the transition to the new FAA rule which required dynamic testing (FAA, 1988). The dynamic test requirements of this new rule are included in Table 19. As part of this transition, a draft Advisory Circular (Chandler, 1988) was written to describe dynamic test procedures, instrumentation, dummy modifications and data interpretation which would be applicable to the new rule. After considering the comments received on this draft, Advisory Circular AC No: 25.562-1, "Dynamic Evaluation of Seat Restraint Systems & Occupant Protection on Transport Airplanes," was issued by the FAA in 1989.

Since certification of seats for large transport airplanes is usually accomplished under the FAA Technical Standard Order (TSO) system, it was also necessary to develop a TSO which included dynamic test procedures and well defined pass/fail criteria. This task was given to the Society of Automotive Engineers. An "Ad Hoc" seat committee was formed in 1987 for the purpose of developing an Aerospace Standard which could be adopted by the FAA as a TSO for certification of seats under the new rule. As of this writing, Aerospace Standard AS 8049, "Performance Standard for Seats in Civil Rotorcraft and Transport Aircraft," is undergoing final review and resolution of comments before being published by the SAE. This comprehensive document includes both static and dynamic test procedures, general design guidance and requirements, strength requirements and detailed criteria for determining if the seat system passed or failed the various tests.

Most of the transport airplane passenger seats which have been dynamically tested in these programs have been intended for forward facing installations in civil aircraft. In 1986, Weber Aircraft initiated a program to develop a rear facing passenger seat which was capable of withstanding the dynamic test loads (Bilezikjian, 1989). Since the primary users of rearward facing passenger seats are the military, this seat was to be consistent with military specifications. Most significantly, it was to be designed for 250 pound occupant weights and required folding legs and seat backs to meet stowing and stacking requirements. Other requirements were that the seat should attenuate the loads on the aircraft floor attachments to levels no higher than would be required to meet static loading criteria. As developed, the seat is an aluminum frame construction with aluminum sheet diaphragms for the seat pan and high seat back. The seat legs are steel tubes, designed to bend during the impact and limit the load transmitted to the floor. An aluminum cross bar spanning the length of the seat, behind the occupants legs, prevents the occupants legs from flailing under the seat during the impact. The total weight of the seat assembly was 93 pounds.[Note 20] The seat was tested at CAMI at 16 G in the longitudinal direction with the seat yawed 10°. A trapezoidal pulse shape, considered more severe than the triangular pulse used for civil seats, was generated in that test. Plastic deformation of the seat legs limited the force acting on the floor to levels equivalent to a 12 G static load.

<u>Transport Crash Studies</u>. The limited understanding of the aircraft crash environment has continued to cast doubt on any attempt to improve occupant protection. In 1967, the Aviation Safety and Engineering Research (AvSER) project completed a study of 61 survivable transport aircraft accidents from 1955 through 1964 and evaluated the data from the FAA (DC-7 and L-1649) and NACA (C-46 and C-82) crash tests (Haley, 1967). Most of the aircraft involved in this study were propeller driven. This study indicated that:

a. Floor decelerations seldom exceeded human limits if proper body restraint was used. The 95th percentile accident would result in peak longitudinal decelerations between 25 G (in the cockpit) and 20 G (in the cabin), with velocity changes of 64 f/s.
b. At least one fuselage "break" occurred in 35 of the 61 accidents studied, and caused injury to passengers at those locations.
c. Seat failures in many accidents were caused by distortion in the leg-to-floor attachments, rather than by excessive deceleration.
d. Improved seat and restraint systems would have reduced or prevented nearly half of the 1037 fatal and serious injuries resulting from these crashes.
e. Reduction of postcrash fires, which occurred in two-thirds of these crashes, would further reduce injuries and fatalities.

A second study, sponsored by the FAA (but assisted by the AvSER project and using much of the same data), was also completed in 1967 (Fitzgibbon, 1967). This study attempted to assess the severity of crash environments through the use of linear shock spectra, and to define a representative crash environment for future crash tests of transport airplanes. The study concluded that the most common survivable crash for large transport airplanes occurred during the landing phase of flight, without roll, pitch or yaw, with an angle of impact of less than five degrees, and with an impact velocity of 166 f/s. Trees were the most common obstacle encountered during a crash. A marginally survivable crash would result if the airplane impacted an embankment of 14 degree slope.

An internal study, preliminary to developing contract requirements for detailed analysis of the crash environment, was conducted by the FAA in 1979 (Chandler, 1982). The Cabin Safety Data Bank at the Civil Aeromedical Institute was queried for survivable accidents or incidents which reported seat or restraint system factors during 1970 through 1978. Twenty-seven ground accidents and three turbulence incidents were identified in this search. Two of the ground accidents were considered to be essentially survivable only "by chance" and were discarded from the study. The fatality rate calculated in this study was less than had been previously reported, but the serious injury rate had not changed significantly. Fuselage floor deformation was found to be a contributing factor to seat failure in 60 percent of the accidents. Turbulence or "hard landings" caused the failure of seats or restraints in 6 of the cases studied.

In 1981, the National Transportation Safety Board issued a study of cabin safety problems in 77 survivable or partially survivable accidents/incidents (including those in flight) which occurred from 1970 to 1980 (NTSB, 1981). Some failure of the various cabin furnishings had been observed in almost 60 percent of those accidents. It was estimated that about 46 percent of the 1850 occupants who were injured or killed would have received less serious injuries had the cabin furnishings not failed. Seat/restraint systems failed in 84.4 percent of the cases. Most of the failures occurred in the seat legs or seat-to-track attachment. In many cases the floor was deformed by localized impacts or bending and buckling of the fuselage. Seat backs, seat pans, frames, arm rests and tray tables also failed. The restraint system failed in 22 percent of the cases, usually at the belt attachment hardware rather than the belt webbing. Overhead racks, panels and passenger service units failed in 78 percent of the cases, and galley equipment failed in 62 percent of the cases.

A special study by Simula, Inc., was included as an Appendix to the NTSB report (Desjardins, 1980).[Note 21] This study suggested new static tests (Table 21) and dynamic tests (Table 22) for seats. Recognizing differences in crash environment and structural energy absorption for different size airplanes, the severity of these tests was adjusted for the size of airplane involved, with more severe tests being suggested for smaller airplanes. These tests were intended to represent the 95th percentile crash environment. In addition, it was recognized that load-limiting designs could be used to provide increased crash protection in retrofit applications without exceeding the structural limitations of existing airframes. Additional tests, shown in Table 23, were suggested as an alternative to the static tests for assessing the performance of load-limiting retrofit seats. Floor warping, in accordance with the procedure outlined in the U. S. Army Crash Survival Design Guide, was suggested to evaluate the seat under the most severe requirements selected for design.

Table 21. Proposed Seat Design and Static Test Requirements

Loading Direction [Note 5]	Required Load Factor [Note 1] with fuselage size designated:		
	Small [Note 2]	Medium [Note 3]	Large [Note 4]
Forward	21	18	15
Lateral	12	10	8
Downward	12±2 [Note 6]	10	8
Upward	8	6	4
Aftward	12	10	8

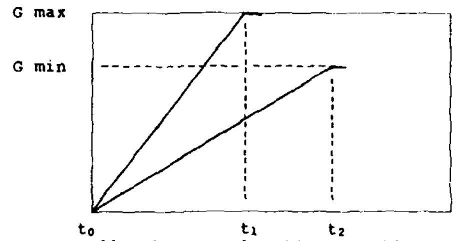
Note 1. The load factors are applied to the sum of seat and occupants weight. Use occupant weights of 220 pounds for single occupant seats, and 170 pounds for multiple occupant seats.
Note 2. Small: less than 36 inches of fuselage structure below the floor.
Note 3: Medium: between 36 and 60 inches of fuselage structure below the floor.
Note 4: Large: more than 60 inches of fuselage structure below the floor.
Note 5: Loading directions are based on the aircraft axis system.
Note 6. An energy absorbing seat is required. The seat should stroke at a load of 12±2 pounds times the combined weight of the seat and the effective weight of a 170 pound occupant, i.e., 136 pounds. The seat should stroke downward for at least 8 inches.

The FAA and NASA LaRC, as part of the preparation for the Controlled Impact Demonstration, issued contracts to Lockheed-California Company, Boeing Commercial Airplane Company, and McDonnell Douglas Corporation for studies of transport airplane crash dynamics. The purpose of these studies was to review available accident data and develop accident scenarios which were representative of the data, to evaluate the effect of advanced materials and construction technology on crashworthiness, to review the U.S. Army Crash Survival Design Guide and the literature pertaining to human tolerance to impact injury, and to make recommendations for future test programs. (The summary presented here will concentrate on the development of accident scenarios.)

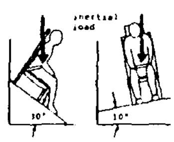
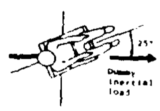
The Lockheed-California study (Wittlin, 1982), reviewed NTSB and Worldwide accident reports from 1964-1977, reviewed crash design requirements and procedures for various transportation systems, summarized injury analysis techniques, reviewed and evaluated previous crash tests, and developed computer models for studies of those data. The study recommended three crash scenarios which were felt to be representative of the crashes studied and which could best provide data for further analysis:

a. A ground-to-ground overrun type accident which occurs at a low forward speed

Table 22. Proposed Dynamic Test Requirements

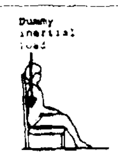


Allowable Acceleration vs. time

Test	Configuration	Parameter	Fuselage Size Note 1		
			Small	Medium	Large
1	 50th Percentile Dummy	t_1, s	0.109	0.128	0.155
		t_2, s	0.147	0.140	0.175
		G min	19	17	14
		G max	22	20	16
		V, f/s	50	50	50
2	 95th Percentile Dummy	t_1, s	0.109	0.128	0.155
		t_2, s	0.147	0.140	0.175
		G min	19	17	14
		G max	22	20	16
		V, f/s	50	50	50

Note 1: See notes 2,3,4, previous table.

Table 23. Additional dynamic tests proposed for retrofit seats which provide energy-absorption to limit floor loading.

Test	Configuration	Parameter	Fuselage Size		
			Small	Medium	Large
3	 50th Percentile Dummy	t_1, s	0.092	0.157	0.196
		t_2, s	0.101	0.168	0.201
		G min	17	10	8
		G max	20	12	10
		V, f/s	36	36	36
4	 95th Percentile Dummy	t_1, s	0.091	0.109	0.136
		t_2, s	0.100	0.116	0.140
		G min	12	10	8
		G max	14	12	10
		V, f/s	25	25	25
5	 95th Percentile Dummy	t_1, s	0.109	0.128	0.155
		t_2, s	0.122	0.140	0.175
		G min	20	17	14
		G max	23	20	16
		V, f/s	50	50	50

(40-130 knots), with the landing gears extended, and the aircraft in a level and symmetrical attitude. Damage is sustained when the airplane traverses a ditch, road or mound. Fuselage breakup is not severe. Longitudinal occupant acceleration is relatively low since it is primarily associated with the ground coefficient of friction.

b. An air-to-ground hard landing accident such as a touchdown just short of the runway. The average sink speed would be about 5.2 m/s (17 f/s). Forward velocity would be from 126 to 160 knots. The airplane lands with gear extended in a symmetrical attitude with nose up 0 to 14 degrees. Major concern for this type of accident is landing gear failure, fuselage break up, fuel tank rupture and seat performance under high vertical loads.

c. An air-to-ground impact on hard ground, with sink speed up to 10 m/s and forward velocity in the range of 126 to 160 knots. The airplane impacts with gears retracted or extended, in an unsymmetrical attitude with 0 to 10 degrees roll and 0 to 14 degrees pitch. Fuselage crush and breakup would be substantial and would limit floor and seat integrity. The potential for fuel tank rupture is high. A wide variety of obstructions in the path of the impact exists.

Because of the wide variety of impact conditions, structural response to the impact, aircraft sizes, speeds and designs, etc., it was recommended that computer analysis would be the most practical approach to assess the effect of the many variables on crash response. It was concluded that the trend is for less accidents, fatal accidents, and fatalities, that the accident performance of jets is better than non-jets, that the emergency landing design requirements are adequate for minor accidents on or around airport runways, but that impacts at high speed or at a large impact angle have a high probability of fatalities.

The Boeing study reviewed 583 transport airplane accidents which occurred from 1959 to 1979. Of these accidents, 275 resulted in hull loss and 214 involved fatalities of passengers and/or crew. After elimination of non-survivable accidents and minor accidents, and detailed review of the cases, 153 potentially survivable accidents were selected for in-depth analysis. Thirty-five percent of the accidents involved fatalities due to trauma, 37 percent involve fire or smoke (some passengers were presumed to have received trauma injury which slowed or precluded egress), and 6 percent involved drowning. Sixty percent of the serious injuries involved trauma, and thirty percent involved fire or smoke. The crashes were categorized into three impact scenarios, shown in Table 24.

Table 24. Range of Initial Crash Conditions (Boeing Study)

Scenario	Velocity, f/s		Roll,	Pitch,	Yaw,
	Forward	Normal	Degrees	Degrees	Degrees
Air to Surface					
Impact other than gear	VS to 321	DS to 70	0 to ?	-5 to 15	? to ?
Impact on gear	73 to VF	? to 60	0 to ?	-16 to 15	? to ?
Impact in water	VS to VF	DS to 33	0 to ?	0 to 15	? to ?
Surface to Surface					
Hard ground	17 to VS	? to 23	0 to ?	0 to ?	0 to ?
Soft surface	101 to 289	0 to ?	0 to ?	0 to ?	0 to ?
Low obstruction	-17 to VR	0 to ?	0 to ?	0 to ?	0 to 45
High obstruction	? to V1	? to ?	0 to ?	0 to ?	0 to ?
Slide into water	67 to 135	0 to DS	0 to ?	0 to ?	0 to 15
Flight into Obstruction					
Wing low	VS to 363	? to 33	0 to 80	-30 to 15	0 to 40
Impact column	VS to VF	? to 33	? to ?	0 to 15	? to ?
Solid wall	VS to VF	? to 100	? to ?	0 to 15	? to ?
High obstruction	VS to VF	? to 33	? to ?	0 to 15	? to ?

Notes: VS = stall speed, DS = design sink speed, VF = flap speed, VR = rotation speed, V1 = decision speed, ? = no data.

The Douglas Study evaluated 109 major fatal, but survivable crashes in the period from 1960 to 1980 (Cominsky, 1982). These were divided into groups of 27 approach, 33 landing, and 49 takeoff accidents. Characteristics of each accident in each group were then listed.

Transport Fuselage Drop Tests. As part of the preparations for the "Controlled Impact Demonstration" (CID) of a Boeing 720 airplane, the FAA and NASA LaRC conducted a series of vertical drop tests to obtain structural response data for computer modeling of the crash. A Boeing 707-101 airplane weighing 195,000 pounds was the test item for a drop test conducted under FAA sponsorship at Laurinburg, North Carolina in June, 1984 (Wittlin, 1985), This airplane was about 100 inches longer than the Boeing 720 airplane used in the CID, but is basically of the same construction and design. The airplane was dropped vertically with an impact speed of 17 f/s, and a +1 degree nose up attitude. The bottom of the airplane crushed about 2 inches aft of the nose gear bulkhead, 4 inches forward of the main landing gear rear bulkhead, and 11 to 13 inches aft of the main landing gear rear bulkhead. The web of the aft main landing gear bulkhead cracked up to the level of the floor. The inboard wing engine pylons failed at the upper strut attachment points. Frame failures, consistent with the fuselage crush, were observed on the lower centerline and along the sidewall. The bulkhead at the wing trailing edge ruptured and pushed the floor up at least 4 inches at that point, severing the transverse beams and seat tracks. Since the seats were unoccupied and not attached to the floor for the test, and floor accelerations were not measured, the potential for seat failure could not be assessed.

Other drop tests used only sections of a fuselage. A 12 foot long section of B-707 airplane fuselage forward of the wing was drop tested at NASA LaRC in April, 1983 (Williams, 1983a). Five three-passenger seat assemblies were installed in the drop test section. The rubberized fabric seat pans in four of these seat assemblies were reinforced by the addition of two aluminum strips, 3 inches wide and 0.1 inches thick, which ran the entire width of the seat. Eight 50th percentile (165 pound) anthropomorphic dummies were placed in these seats. Three seats had only one dummy, which was placed in the center seat. One seat had two dummies placed in the center and outboard seats. The seat without seat pan reinforcement was fully occupied by three dummies. Ballast weights (146 to 217 pounds) were placed in the unoccupied seats. The seats, dummies and other articles and ballast located on the cabin floor raised the weight of the section to 5051 pounds. The section was dropped in a flat orientation (no roll or pitch) with an impact velocity of 20 f/s. Bending failure of the fuselage frames occurred on both sides of the fuselage at approximately one third of the vertical height from the fuselage bottom to the top of the floor, and the floor of the baggage compartment buckled inward and upward at the center, so that the fuselage cross section took on a cardioid shape. The maximum normal acceleration on the bottom of the fuselage was about 20 G (20 Hz filter) and lasted about 0.03 s. Acceleration levels dropped soon after the buckling failure and increased again to a maximum of 12 G as the structure stiffened. No damage occurred to the upper fuselage, floor or seats during the test.

A 13 foot long section of B-707 airplane fuselage from just behind the wing and including the wheel wells, keel beam and part of the rear wing spar was drop tested at NASA LaRC in June 1983 (Williams, 1983b). Four three-passenger seat assemblies were installed in the drop test section. Eight 50th percentile (165 pound) anthropomorphic dummies and one 95th percentile (195 pound) dummy were placed in these seats. One seat assembly had two dummies placed in the center and outboard seats. Two seat assemblies had dummies in the center and inboard seats. One of the dummies in an inboard seat was the 95 percentile dummy. One seat assembly was fully occupied by three dummies. Ballast weights (147 pounds) were placed in the unoccupied seats. The seats, dummies and other articles and ballast located on the cabin floor raised the weight of the section to 7964 pounds. The section was dropped in a flat orientation (no roll or pitch) with an impact velocity of 20 f/s. This stiff fuselage section did not deform significantly during the test. Consequently, loads were transmitted from the lower fuselage into the floor, upper fuselage, seats, and dummies. The lateral tubes which cantilever the inboard seat position broke at those seat locations which were loaded with ballast. The fabric seat pans tore loose from their attachment to the seat frame in those seats occupied by dummies. The maximum normal acceleration measured on the keel beam and wheel wells was approximately 71 G (60 Hz filter) for a duration of 0.019 s. Maximum accelerations measured on the floor ranged from 70 to 95 G, with durations of 0.022 to 0.017 s, respectively.

A 10 foot long section of B-707 airplane fuselage from just aft of the landing gear wheel well to forward of the rear galley was drop tested by the FAA Technical Center (Johnson, 1986). Three rows of three place passenger seat assemblies (six seat assemblies) and overhead baggage racks were installed in the section. Four 180 pound anthropomorphic dummies and two 150 pound cardiopulmonary resuscitation (CPR) type dummies were placed in the seats. Each seat in one seat assembly in the middle row was occupied by anthropomorphic dummies. The other seat assembly in the middle row was occupied by one anthropomorphic dummy in the center seat, and the CPR dummies in the other two seats. Empty seats were loaded with 150 pound ballast weights. The two overhead bins contained 13.5 pound ballast weights to simulate carry-on baggage. The cargo compartment below the floor was filled to capacity with baggage. The cargo door was pinned in place. The total weight of the section was 8,883 pounds. The section was dropped in a flat orientation with an impact velocity of 34 f/s. The lower fuselage shell and loaded cargo compartment crushed 2 to 3 feet during the impact. Multiple failures of the fuselage frame members occurred, with more damage on the side of the fuselage which was not reinforced by the cargo door frame and door structure. The cabin fuselage and floor structure showed no damage. Average accelerations in the cabin ranged from 6 to 10 G, with durations of 0.11 to 0.17 s. The legs and cross tubes of the passenger seats bent or buckled, but the seats remained attached to the floor. The seat occupied by the anthropomorphic dummies received the least amount of damage. The overhead baggage compartments were undamaged.

A 12 foot long section of B-707 airplane fuselage from the forward passenger cabin was drop tested by the FAA Technical Center (Pugliese, 1984). Four three place passenger seat assemblies, occupied by a combination of dummies and ballast, and a lower cargo compartment filled with 1860 pounds of baggage raised drop weight to 6,440 pounds. The section was dropped in a flat orientation with an impact velocity of 20 f/s. The lower part of the fuselage and the cargo compartment crushed 17 to 20 inches. Maximum accelerations on the cabin floor ranged from 18 to 25 G, with durations of 0.079 to 0.085 s, respectively.

The FAA also conducted two wide body (DC-10) airframe section drop tests (Arvin/Calspan, 1984, Caiafa, 1988). One test was conducted without cargo. The test section weighed about 5000 pounds, and the impact velocity was 20 f/s. Fuselage crush was minimal, ranging from 1 to 2 inches. Accelerations on the floor ranged from 30 to 40 G, with durations of 0.03 to 0.042 s. The second test was conducted with 5,100 pounds of cargo in two containers, so the section weight was 10,800 pounds. The impact velocity for this test was 25 f/s. Fuselage crush ranged from 11 to 15 inches. Maximum acceleration on the floor was approximately 15 G, with a duration of 0.09 s.

The Controlled Impact Demonstration B-720 Crash Test (CID). For over 20 years, the United States Federal Aviation Administration (FAA) conducted a program to evaluate the performance of fuel additives which would decrease the incidents of fire in transport aircraft crashes. It was believed that the post-crash fireball resulting from ignition of fuel spilled during crash deceleration, wing break-up and fuel tank rupture resulted in a high percentage of fatalities. Over 300 wing spillage tests and six catapult tests of obsolete military aircraft were conducted. A high molecular weight polymer, FM-9, had been developed which, when blended into jet fuel, formed a slurry which prevented the fuel from taking the form of a highly flammable mist as it escaped from fuel tanks ruptured in a high speed impact. Instead, this anti-misting kerosene (AMK) fuel would retain the form of rather large droplets as it escaped from the ruptured tanks. It was shown that these droplets resisted ignition much better than the fine mist, and thus reduced the fire hazard.

The FAA made a commitment to the U.S. Congress to demonstrate the performance of AMK fuel and other crashworthy technology through a full scale, air-to-ground crash test of a transport airplane (Anon, Mgt plan, 1984). The National Aeronautics and Space Administration (NASA) agreed to cooperate in this effort with the Langley Research Center and the Ames Research Center Dryden Flight Research Facility. The FAA Technical Center in Atlantic City was to act as Program Manager and primary experimenter for the AMK fuel system and certain crashworthiness and fire safety demonstrations. NASA LaRC would maintain a primary role in transport crash behavior experiments and provide the instrumentation and data acquisition system. The Dryden Flight Research Facility would have responsibility for systems and experiment integration, flight control and operations. The various impact demonstration experiments planned for the crash are shown in Table 25.

The airplane selected for this test was a Boeing 720 four engine intermediate range jet transport. The airplane had been in service with the FAA since 1960, and had logged over 20,000 flight hours and over 54,000 takeoffs and landings. The airplane was turned over to the Dryden Flight Research Facility in June, 1981, for test preparation. Interior materials, floor covering and side panels were removed to install the instrumentation and the interior test items. The flight deck system was modified to permit remotely controlled flight. Fuel systems were modified and AMK fuel degraders, necessary to allow engine operation with the AMK slurry, were developed and installed. Air conditioning and pressurization turbocompressors were removed from the engines to allow installation of the AMK degrader system. Anti-icing systems for the wing leading edges were eliminated. Dual flame generators were installed in the tail cone to provide a positive ignition source for the AMK fuel. Three hundred and fifty instrumentation transducers were installed and connected to the data recording system for the various on board experiments. Two rows of heavy steel wing cutters (designed to assure spillage of the antimisting fuel at 20 to 100 gallons per second) and a bed of coarse stone and frangible landing lights (to provide a spark ignition source during slide out after impact) were installed at the impact site.

The FAA seat experiment began with static and dynamic tests to destruction of standard Weber P/N 819483, Weberlite 4000, and UOP Model 901 three place passenger seat assemblies (Cannon, 1986). The Weber P/N 819483 seat was used on many early narrow bodied aircraft such as the 707, 720, and DC-8. It has a tubular steel leg assembly typical of many seats. A later design, the Weberlite 4000, is similar in appearance but about 30 pounds lighter, weighing about 55 pounds. The UOP Model 901 is also a lightweight seat, but uses sheet metal leg construction rather than tubes. Trans-Aero

Table 25. Experiments for the Controlled Impact Demonstration (CID)

ANTIMISTING KEROSENE (AMK)	VERIFY AMK CAN PRECLUDE IGNITION DEMONSTRATE AMK IN OPERATIONAL FUEL/PROPULSION SYSTEM
WING, FUSELAGE, AND FLOOR STRUCTURE	EXAMINE STRUCTURAL FAILURE MECHANISMS AND CORRELATE ANALYTICAL PREDICTIONS PROVIDE BASELINE METAL CRASH DATA TO SUPPORT FAA AND NASA COMPOSITE CRASH DYNAMICS RESEARCH. DEFINE DYNAMIC FLOOR PULSE FOR SEAT/RESTRAINT SYSTEM STUDIES
SEAT/RESTRAINT SYSTEM	ASSESS REGULATORY CRITERIA EVALUATE PERFORMANCE OF EXISTING, IMPROVED AND NEW LIGHTWEIGHT SEAT CONCEPTS EVALUATE PERFORMANCE OF NEW SEAT ATTACHMENT FITTINGS
STOWAGE COMPARTMENTS AND GALLEYS	EVALUATE EFFECTIVENESS OF EXISTING AND IMPROVED RETENTION MEANS
ANALYTICAL MODELING	VALIDATION OF "KRASH" AND "DYCAST" COMPUTER MODELS OF TRANSPORT AIRCRAFT VERIFY PREDICTED CRASH TEST IMPACT LOADS
CABIN FIRE SAFETY	SEAT CUSHION BLOCKING LAYERS BURN THROUGH RESISTANT WINDOWS
FLIGHT DATA AND COCKPIT VOICE RECORDERS	DEMONSTRATE AND EVALUATE PERFORMANCE OF NEW SYSTEMS DEMONSTRATE USEFULNESS FOR ACCIDENT INVESTIGATION
ACCIDENT INVESTIGATION	ASSESS ADEQUACY OF CURRENT FORMS AND INVESTIGATION PROCEDURES

Model 90835-4 flight attendant seats were also obtained. These were considered typical of modern flight attendant seats. A Hardman/UOP Model 9777 double occupant aft facing seat, a UOP Model 910 seat similar to the model 901 but with a composite material seat pan, and a seat manufactured by Sicma Aero Seats, Inc., of France were also installed in the aircraft, but were not a part of the static/dynamic test program or the modification program.

Static tests indicated that the seats could resist the 9 G equivalent force required by the regulations. Dynamic tests, conducted by FAA-CAMI, caused all the seats to fail when exposed to a 9 G, 50 f/s impact having a trapezoidal pulse shape which was of sufficient duration to achieve maximum dynamic response (loading) of the seats. After these tests, a modification process was begun with the goal of increasing the strength of the seats to accommodate 18 G forward, 10 G sideward, 10 G downward and 6 G upward. Corresponding dynamic impact criteria were also developed. It was intended that changes made in this modification process would not render the seat impractical because of general configuration, weight, cost, comfort, stowage space, foot clearance, etc. The modifications were designated as:

Weberlite Mod. Energy absorbers replaced the seats rear legs and diagonal struts. Stronger front legs and lateral bracing were added. Seat weight was 68 pounds.

UOP Mod I. The diagonal struts were replaced with compression energy absorbers and stronger rear legs were installed. Front legs were extended and reinforced to attach to track fittings which provide roll release by bending. The seat weighed 67 pounds.

Weber Mod I. The restraint system was modified so the lap belts actuated an energy absorber. A reinforced leg structure replaced the original seat legs, and stronger seat pans replaced the original components. The seat weighed 100 pounds.

UOP Mod II. Energy absorbers replaced the seats rear legs, a stronger diagonal strut was used, and the front legs were extended and reinforced. The seat weighed 67 pounds.

Weber Mod II. The entire seat leg assembly was replaced with a stronger assembly having energy absorbers as rear legs. The seat pan was also strengthened. The seat weighed 89 pounds.

Weber Aft Mod. A P/N 819493 was extensively modified to aft facing configuration. Reinforced seat backs were installed with appropriate support bracing, and a reinforced seat leg structure was installed which incorporated energy absorbers in the front (aircraft front) legs. The seat weighed 88 pounds.

Trans Aero Mod. The pivot arm bracket, pivot arm assembly, and seat pan roller bracket were reinforced. Seat weight increased by 2.8 ounces.

The NASA seat experiment used Fairchild Burns Airest 2000 seats. Both standard and modified seats were placed in the aircraft. The modifications converted the standard seat into an energy absorbing seat by replacing the diagonal members in the leg assembly by energy absorbers, and by allowing the seat legs to rotate around the seat frame cross tubes, as in a parallelogram linkage, to allow the seat to stroke downward and forward.

Because the AMK fuel was intended to prevent the formation of fine mist by fuel discharged from a ruptured tank, the crash conditions were selected to create an environment most likely to generate a fuel mist. This required rupture of the fuel tanks at high speed, and then sustained high speed to promote the formation of a fuel mist as air passed over the ruptured tank. It was decided that the aircraft should impact with a sink rate of 15 to 20 f/s, with a glide path of 3.3 to 4 degrees, a nose up pitch of 0 to 2 degrees, a longitudinal impact velocity of 145 to 155 knots, with ± 1 degree of roll and yaw.

The requirement that airspeed be maintained after initial impact and rupture of the fuel tanks dictated that the longitudinal deceleration level be kept low during the crash. Pre-test estimates of the crash environment indicated that peak vertical decelerations might reach 12 G in the nose of the aircraft but should be 10 G or less throughout the remainder of the cabin. Longitudinal deceleration should be 4 G or less (Soltis, 1985). Since this was well below the design levels of the experimental seats, post-crash dynamic testing of the seats at FAA-CAMI was anticipated.

The crash test was conducted on December 1, 1984. The airplane was fueled with 11,325 gallons of AMK fuel. During final approach to the crash at 200 feet altitude, the aircraft was slightly low and had a right lateral deviation from the intended flight path. The pilot of the remote control system, thinking he could correct this deviation, continued the approach. A project guideline had established that once the airplane went below 150 feet in altitude, the pilot was committed to impact. The deviation had not corrected as the airplane passed the 150 foot altitude level, and the pilot increased his correction. However, there was insufficient altitude and time for the airplane to recover and the crash occurred off target.

The left outboard engine first impacted the ground, with the airplane in a slight nose down attitude. The impact was short of the target contact point, and the airplane was in a slight yaw to the left. The left inboard engine then contacted the ground, followed by the initial fuselage impact. The aircraft continued to yaw to the left during slide out, and came in contact with the first wing cutter (placed to cut open the fuel tanks in the intended crash) at a yaw angle of about 38 degrees. The cutter passed through the right inboard engine, hit the leading edge of the wing and diagonally slashed the lower wing skin back to the mid- hord, leading to the failure and separation of the right wing. Immediate ignition of the engine fluids took place as the cutter contacted the engine. Antimisting kerosene, engine oil, and hydraulic fluid continued to burn throughout the slideout, with the engine acting as the main flame holder. Fuel, under pressure, was fed onto the hot engine surfaces, increasing the intensity of the fire. The right front cargo door opened on impact, providing an opening for burning fuel to enter the fuselage. A second wing cutter then impacted the inboard leading edge of the right wing, slashed diagonally through the lower wing skin to the right main gear wheel well. Part of this cutter broke off, and was found in the lower aft cargo compartment. Another cutter impacted the leading edge of the right wing and slashed diagonally to the rear, passing through the lower center wing box, penetrating the left main gear wheel well, and tearing out the keel beam so that burning fuel could enter the fuselage from the bottom. The far right cutter passed through the inboard trailing edge of the right wing, and then cut diagonally through the lower aft fuselage. This provided one more opening for burning fuel to enter the fuselage. The aircraft came to rest approximately 10 seconds after the initial impact. Fuel continued to be discharged from the tanks and burn. Fire trucks were on the scene within two minutes after the aircraft stopped, but the fire continued to burn for over one hour.

The antimisting function of the fuel additive did not play a significant part in this crash sequence. The initial fire occurred in the immediate area of the wing tank rupture as engine fluids contacted hot engine surfaces. This resulted in vaporization and ignition of the fuel before misting could occur. It was shown that the engines, with degraders, could operate normally on AMK fuel, but it was also shown that there are crash conditions where adding an antimisting characteristic to jet fuel will not prevent a post-crash fire.

The fire destroyed large sections of the fuselage, and many of the experimental seats in the fuselage. The instrumentation system was protected from the crash environment, and provided acceleration data throughout the impact. However, peak seat accelerations exceeded 10 G only in the flight deck section of the aircraft, where the normal acceleration reached 14 G and the longitudinal acceleration reached 10 G. Normal seat accelerations in the cabin from the third row back were all well under 10 G, and longitudinal accelerations quite low, often not exceeding 2 or 3 G. Although the airplane was rolled and yawed at impact, transverse accelerations were under 2 G in many locations, and ranged only from -2 to 5 G. (Fasanella, 1986).

Visible inspection of the seats which survived the fire showed no noticeable deformation or fractures which could be related to the impact environment. Unfortunately, the exposure of the surviving seats to the heat of the fire could cause undetected degredation, so that sled testing of those seats was not warranted.

Longitudinal Impact Test of a Transport Airplane Fuselage Section. A 10 foot long section of a Boeing 707 fuselage was tested on the horizontal HYGE accelerator at the Transportation Research Center of Ohio in October, 1987. (Johnson, 1988a, 1988b). The purpose of this program was to measure the loading between the aircraft floor and the passenger seats during a longitudinal impact. The 10 foot section of fuselage was taken from just forward of the rear galley of the B-707 airplane. To compensate for the open ends of the section and to compensate for the inadvertent removal of the under floor cargo liner attachment members, the floor structure was modified by reinforcing the end floor beams by attaching an additional beam below the existing beam, and by tying the reinforced end beams to the existing beams with five longitudinal stringers running under the beams for the full length of the section. In addition, the number of floor panel attachment fasteners on the outboard floor panels were doubled to provide additional shear strength. The fuselage was instrumented with accelerometers, strain gages, displacement potentiometers and crack detector wires.

Six three-passenger seat assemblies were installed in the fuselage section. These seat assemblies, originally designed for "9 G static loads", were reinforced to withstand the anticipated dynamic loads. Previous testing at the FAA Civil Aeromedical Institute (CAMI) had defined those areas in need of reinforcement. The reinforcement included the addition of gussets joining the front and rear cross tubes of the seat with the seat legs and the local filling of the cross tubes at the leg and spreader attachment areas with rigid epoxy to preclude collapse under load. The seat assemblies were rigid, without significant energy absorbing characteristics, and weighed 105 pounds each. The seat legs were made of thin wall steel tubing of rectangular cross section. Strain gages were located on the front and rear legs and on the diagonal member running from the upper front leg to the lower rear leg. These strain gages were calibrated in terms of the leg to floor reaction loads in dynamic tests at CAMI (Gowdy, 1988). Each seat assembly was fully occupied by 50th percentile (164-167 pound) anthropomorphic dummies for the test. Total weight of the test section, seats and dummies was 5498 pounds.

The first test generated a longitudinal acceleration of 7.4 G with a velocity change of 22.4 f/s. This test was conducted to check the test setup and verify the data ranges. The second test generated a longitudinal acceleration of 14.2 G with a velocity change of 36.2 f/s. The maximum accelerations measured at the fuselage floor were in the 14 to 15 G range. The cabin fuselage shell and floor structure were undamaged. Minor buckling was observed on the legs and cross tubes of the passenger seats, but the seats remained intact and in place and restrained the dummies. Head and leg contact from the anthropomorphic dummies was noted on the backs of seats in the first and second row (there were no dummies seated behind the third row). The maximum measured deflection of the floor track varied between 0.35 and 0.66 inches during the test. There was no permanent floor track deformation attributed to the test.

Joint U.S. Army, Navy and FAA Programs. Cooperative programs were undertaken in an attempt to better understand the techniques used for evaluating vertical (+ G_z) energy absorbing seats (Coltman, 1982). The variables examined in this study were:

a. Test facility impact conditions.
b. Magnitude of input deceleration.
c. Velocity change.
d. Rate of onset of input acceleration.
e. Dummy type.
f. Dummy percentile.
g. Cadavers versus anthropomorphic dummies.
h. Energy absorber limit load.
i. Ramped energy absorbers.
j. Movable seat weight.
k. Seat frame stiffness.
l. Seat cushion stiffness.
m. Seat orientation to impact vector.

Four test facilities were used in this program. The FAA Civil Aeromedical Institute operated a horizontal decelerator sled which used wire-bending energy absorbers to generate the impact pulse. The pulse shape generated by this facility is characterized by a smooth shape with only about five percent of the velocity change occurring in rebound. The Naval Air Development Center operated a drop tower which uses steel straps pulled over rollers to decelerate the carriage. The impact pulse shape produced by this facility has a distinct oscillation with a short duration initial peak followed by a reduction below zero and then the major deceleration pulse. Simula, Inc. (under U. S. Army sponsorship) used the Arizona State University drop tower. Deceleration is provided by a pyramid shaped stack of paper honeycomb. This facility produces a smooth impact pulse with about 25 percent of the velocity change due to rebound. The Wayne State University WHAM IV test facility is a horizontal sled which is decelerated by regulating the flow of hydraulic fluid through a series of orifices. This facility produces a smooth impact pulse with significantly higher rate of onset than either the CAMI or Simula facilities. A minimal amount of the velocity change is due to rebound. Fifty tests were conducted at CAMI. Twenty-three were tests with a rigid seat and twenty-seven used energy absorbing crew seats. NADC and Simula conducted nine and three tests, respecitively, all with an energy absorbing seat. The Wayne State University facility was used for cadaver testing.

The following conclusions were based on the data collected in this program.

a. The shape of the input acceleration pulse has a significant effect on the seat and occupant response.

b. Different test facilities will produce different results in terms of seat and occupant response. Differences can be attributed to test orientation (horizontal or vertical) and the characteristics of the pulse shape.

c. Measurement of spinal force and moment provides the most reliable means of relating test performance to spinal injury. Seat pan acceleration is not a good indicator of test severity or injury potential.

d. Stroke distance and energy absorber limit load are not linearly related. The required stroke distance increases more rapidly than a reduction in limit load would indicate.

e. Energy absorbers with an increasing ramp load-stroke characteristic are less efficient than constant load energy absorbers, and are potentially hazardous to the occupant.

f. Placement of dummy feet can significantly influence seat and occupant response in a dynamic test.

g. The (automotive) "Part 572" dummy provided repeatable results and showed no measurable degradation during the tests. However, the response of the elastomeric spine of the dummy is unlike that of a human spine.

h. The preload produced by low level pre-impact acceleration, such as might be provided by energy absorbing landing gear, can reduce the magnitude dynamic "overshoot", and lower the peak accelerations and loads in the body.

Fifteen tests were conducted with unembalmed cadavers by Wayne State University. An estimated spinal injury rate was linearly correlated with the effective energy absorber limit load according to the following relationships (Coltman, 1985) :

For the U.S. Adult Civil Flying Population,

Spinal Injury Rate (percent) = 9.64 (Effective E/A limit load, G) - 95.47.

For U.S. Army Aviators,

Spinal Injury Rate (percent) = 7.01 (Effective E/A limit load, G) - 81.0.

Special Topics.

Boeing Cabin Crew Restraint System. The Boeing Commercial Airplane Company initiated a review of restraint systems for cabin crew on large transport airplanes as a result of concerns expressed that the safety belt anchorage fittings were sometimes located above the seat reference point and would thus promote submarining. The crew restraint systems in question were "4-point" restraints composed of dual shoulder belts joined to the center of the safety belt at the buckle. Dynamic tests at CAMI indicated that submarining could take place with these installations if the occupant were small in size (tests were done with a fifth percentile female dummy) and the restraint system was not tight prior to the impact. The obvious solution to the problem, lowering the safety belt anchorage points, was not feasible because of the significant costs associated with retrofiting existing airplanes and because of possible interference with the folding crew seat mechanism in some installations. The solution of adding a seat belt tie down strap between the seat belt buckle and the seat pan was not feasible because the structure and design of the folding crew seats in service would not withstand the forces applied by the strap. Analysis of film data from the tests and computer modeling indicated that the submarining was initiated when the shoulder belts pulled the safety belt up, off the dummy's pelvis into the abdominal area. A new restraint system was developed with dual shoulder belts in the form of an inverted-V, with the apex of the "V" fastened to the bulkhead behind the crewmember's neck and with the lower ends of the shoulder belts passed through the seat belt end fittings and then stitched to the safety belt midway between the end fittings and the buckle. Since the shoulder belts no longer pulled the safety belt up, the problem of potential submarining was eliminated. Release of the safety belt would allow the segment of shoulder belt webbing stitched to the safety belt to pull through the safety belt end fitting. The shoulder belts could then be slipped off the shoulders for rapid egress from the seat. For this action to take place, the safety belt must be adjusted to a snug fit before the shoulder belts are adjusted when donning the restraint. Dynamic tests and computer analysis confirmed the performance of this system during impacts. This restraint system is often referred to as the "Boeing 5 point restraint" or the "TARC" restraint (Parks, 1979). The restraint has been fitted to most cabin crew seats in Boeing transport airplanes.

Side Facing Seating. Numerous studies have attempted to develop improved side facing seat and restraint systems. Most often these studies recommend some form of distributed load restraint system, such as a webbing net or a padded bulkhead, to restrain the upper torso. Alternate recommendations often include a rotation seat to re-position the occupant in a more desirable forward or rearward facing position to withstand the impact (Reilly, 1975). If space permits, and if the occupant is sufficiently self disciplined to rotate the seat into the forward or rearward facing position whenever the ground is approached, such a system could be advantageous. However, self-aligning seats which are designed to automatically rotate into position during the crash have not yet proved feasible. The short duration of the crash, and the relative high rotational inertia of the seat and occupant, typically cause the seat rotation to take place after the crash impact is over, so that no benefit is gained by the self-aligning seat. Moreover, once the seat rotation takes place, it must be stopped, so that the occupant is exposed to two impact pulses, with increased danger of injury. Other studies have suggested complex "encapsulating" seat/restraint systems which might be somewhat effective for protection of injury in lateral impacts (e.g. Freeman, 1962), but these systems have not proven practical for normal operational use.

Lateral flailing of the head and legs are among the more serious unresolved and persistent problems of practical side facing seat and restraint systems. Lateral flailing of the head can generate high bending and torsional loads in the neck. Lateral flailing of the legs can introduce twisting of the spinal column and misalignment of the vertebrae. These actions seriously degrade the ability of the spinal column to accommodate vertical impacts, so the possibility of serious, non-reversible spinal injury is increased. Until these problems can be resolved in a practical manner, the side facing seating position can only be considered "non-crashworthy."

Child Seat and Restraint Systems for Aircraft. Even though there are few child or infant fatalities in crashes of commercial transport airplanes, restraint systems for infants and small children in transport airplanes have been a concern for many years. The experiments with child restraint systems in the AvSER crash tests of transport airplanes in 1964 have already been discussed. Similar concerns exist in military transport systems which provide for travel of dependent families with young children. The supplementary belt for infants held in the lap of an adult passenger was developed in 1964, and has seen occasional use since that time. This infant belt is nothing more than a standard seat belt extension with an additional small loop of webbing sewn cross-wise near its midpoint. (A seat belt extension is a length of webbing with a latch plate on one end and a buckle and adjustor on the other. It is used by operators of transport airplanes to extend the length of the normal seat belt for obese passengers.) The infant belt is placed around the waist of the child, and the adult's seat belt is passed through the loop of the infant belt, and then fastened. Unfortunately, the infant belt concentrates crash loads on the child's waist. In a severe crash, this can cause serious injury to the child. In an unanticipated crash, where the adult is seated upright, the adult's body may flail around the seat belt and impact or crush the infant. In one recent dynamic test of the infant belt at CAMI, the adult dummy's head impacted the child dummy's head and forced it into the seatback in front of them, an action likely to have caused serious injury to an infant. The infant seat belt is also subject to a number of forms of misuse. For example, the instructions given for crash preparation by one operator of transport airplanes showed the infant, in the belt, laying in the adult's lap, facing rearward. In such a position the infant would hyperextend around the infant belt in a serious crash, with a very high probability of irreversible injury or death.

Seat and restraint systems for infants and small children in automobiles have received extensive development. In 1982, the FAA announced that suitable automobile child seat and restraint systems could be used on the civil aircraft under its jurisdiction. This action gave permissive approval, but did not require the use of special child restraints. Automobile child restraint systems must be fastened into and adult seat. Mandatory use of automobile child seats in commercial aircraft would most likely require the purchase of seat space for the installation of the child seat. This could significantly increase the cost of travel in commercial transport airplanes for families with small children. A mandatory requirement for use of automobile child seats in civil transport aircraft could not pass the "cost vs. effectiveness" criteria required for rulemaking in the United States. Perhaps more important, it was feared that the higher cost of airline travel for families with small children could result in increased automobile travel by those families, and thus result in an overall greater risk of injury for those children.

Injuries to small children which occur in flight through turbulent air conditions is an associated problem which should be considered. Although reliable data are not available to make a comparison, it appears that more children are injured in turbulence

incidents than in crashes in commercial aircraft. An optimum child restraint system for small children would be effective in both turbulence and crash conditions. One of the problems in achieving that goal is that the restraint must be worn by the child throughout the flight, so that it will offer protection in unanticipated turbulence. Any restraint which is uncomfortable or restricts the activity of the child or the adult (with the infant belt) is unlikely to be worn throughout a long flight.
To the best knowledge of the author, only some automotive infant restraints which also serve as infant carriers or infant beds are likely to be properly used throughout a long aircraft flight.

One form of automobile child seat which may not have utility in an aircraft is the "child booster seat." These devices are fairly recent developments, and place the child in better sitting position relative to the seat belt installations found in many automobiles. In an aircraft passenger seat, the seat belts are usually positioned so that it is unnecessary to raise the child's sitting position for proper fit of restraint systems.

At the time of this writing, a fully satisfactory restraint for the child held in the lap of an adult has not been produced. Prevention of injury to other passengers by an unrestrained child in a crash has been given as the primary justification for using the infant belt. It would appear that the automobile child seat and restraint system, properly fitted to an adult seat, presently offers the best protection for a small child in a crash. If the cost of providing the adult seat is not an issue, automobile child seats provide the best option for protecting children in an aircraft at the present time.

Human Factors in Crash Protection. The development of occupant crash protection systems has progressed from simple seats and belt type restraints which could be evaluated by equally simple static strength tests, to increasingly complex energy absorbing seating and restraint systems with powered reels or airbags which actuate at the beginning of the crash event. The design of these devices has been further complicated by the wide variation in anthropometric measures of the occupants of the systems, particularly with the increasing participation of women as crewmembers on board aircraft. Table 26 provides selected anthropometric data for U.S. Army personnel. From these data, it can be seen that a design which would accommodate the fifth through ninety fifth percentile male occupants may be too large for about half of the potential female occupants. Operational requirements may make this an unacceptable design. For the seat designer, the critical dimensions are those which govern the eye point, the heel point, the contact point of the shoulder restraint on the shoulder, the various body girths which establish the range of adjustment required for the restraint system, the functional reach measurements which allow access to aircraft or seat controls, and those length, breadth and height dimensions which limit the seating surfaces. The range of occupant weights, wearing either light summer clothing or cold weather clothing and required flying equipment, should be considered in establishing the requirements for vertical seat energy absorption. Strength capabilities of the intended occupants should be considered when specifying requirements for releasing the restraint system or opening exits for emergency egress.

The "Brace for Impact" Position. The purpose of positioning the body in preparation for an impact is to lower the chance, or level, of trauma. However, the muscular strength of a human is sufficient only to support the body under 3 or 4 G, so muscular strength is useful under relatively low crash loads. Several dynamic impact tests have been conducted at CAMI to evaluate the effectiveness of bracing for impact (Chandler, 1985, 1988) in more serious crashes. In these crashes, the goal of bracing for impact should be to position the body against whatever it might hit during the crash, and thus eliminate the "second impact." The best position for each occupant of an aircraft will depend on the crash environment, required duties of the occupant at the time of the crash, the interior configuration of the aircraft within the strike envelope of the occupant, the design of the seat and restraint system being used, and the size and physical condition of the occupant. With so many factors involved, there is no single "brace for impact" position which is best. However, based on those factors which can be predetermined, appropriate guidelines for some common configurations can be suggested;

a. Forward facing seat with only safety belt restraint:

   Move back into the seat, pull the safety belt tight, lean forward and rest the folded arms and head against the seat back in front. If there is no seat back or other structure within flailing distance, rest the chest on top of the legs, wrap the arms under the legs, and bend the head down.[Note 22]

b. Rear facing seats:

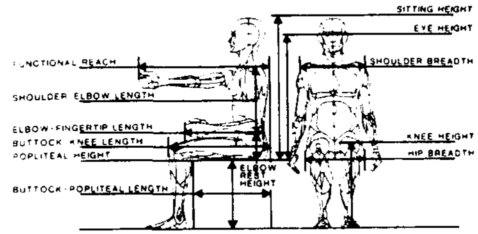
   Move back into the seat and pull the safety belt tight. Sit upright with the head firmly against the headrest. Arms should be placed on the armrests if they are available and properly positioned. Clasp hands together and place them in front of the waist.

c. Forward facing seats with seat belt and shoulder harness.

   Move back into the seat and pull the safety belt and shoulder harness tight (if possible). Lock the webbing take up reel on the shoulder harness, if possible. Flex the head forward as much as possible, and keep it down. Clasp the hands firmly together, and place them in front of the waist.

Table 26. Anthropometric Measurements of U. S. Army Personnel.

Measurement	Percentiles, inches								
	Male Aviators			Male Soldiers			U.S. Army Women		
	5th	50th	95th	5th	50th	95th	5th	50th	95th
Weight, pounds	133.0	171.0	212.0	126.0	156.0	202.0	102.8	131.4	164.3
Stature	64.6	68.7	72.8	64.5	68.7	73.1	60.1	64.1	68.5
Seated height	33.7	35.8	37.9	33.3	35.7	38.1	31.1	33.5	35.8
Shoulder breadth	17.0	18.7	20.3	16.3	17.8	19.6	15.1	16.5	18.0
Functional reach	28.8	31.1	34.2	-	-	-	25.2	28.0	31.1
Sitting hip breadth	13.2	14.8	16.7	11.9	13.0	14.5	12.4	13.9	15.6
Sitting eye height	29.0	31.0	33.1	28.6	31.0	33.3	26.7	29.1	31.2
Sitting knee height	19.3	20.8	22.6	19.6	21.3	23.1	18.5	20.0	21.8
Sitting elbow rest height	7.4	9.1	10.8	-	-	-	6.4	8.2	9.9
Popliteal height	15.1	16.6	18.3	16.0	17.5	19.2	15.0	16.4	18.0
Shoulder-elbow length	13.3	14.4	15.6	13.3	14.5	15.7	12.1	13.2	14.4
Elbow-fingertip length	17.6	19.0	20.3	17.4	18.8	20.4	15.7	17.1	18.7
Buttock-popliteal length	17.7	19.3	21.0	18.0	19.6	21.3	-	-	-
Buttock-knee length	22.0	23.7	25.4	21.6	23.4	25.3	20.9	22.7	24.9



Anthropomorphic Dummies. With current knowledge, it is necessary to demonstrate the performance of crashworthy seat and restraint systems through dynamic testing in which anthropomorphic dummies are used as surrogates for human occupants. Unfortunately, the anthropomorphic dummies available for use in these tests are poor representations of the human. Most of the dummies which are used to test fixed (non-ejection) seats in aircraft are dummies which were developed for use in automobile testing. These have been standardized to provide reproducible results, but the standardized dummies are available only in the size of the nominal "50th percentile male." Dummies in other sizes are standardized only to the extent desired by their manufacturer. Considerable effort has gone into the development of automotive dummies to improve their response and biofidelity of impacts which take place in a horizontal plane, but virtually no effort has been made to improve their response to vertical impacts. More recent automotive dummies have been designed to represent the casual "slumped" posture of the automobile driver, and may not adequately represent the (more likely) erect seated posture of the pilot of an aircraft about to crash.

The Advanced Dynamic Anthropomorphic Manikin (ADAM) is a dummy being developed by the U. S. Air Force for ejection seat testing. This sophisticated dummy is designed to provide increased biofidelity (human like) characteristics for mass distribution, anthropometric dimensions, and dynamic response in the vertical direction. However, this dummy is in very limited production, and the cost of the dummy is far beyond the resources generally available for testing fixed aircraft seats.

An inherent requirement for a modern dummy is the ability to interpret measurements made in the dummy as an indication of a human injury. The definition of injury criteria is a complex process, requiring the comparison of measurements made on the anthropomorphic dummy with data from laboratory tests with volunteer subjects, cadavers and animals, and with the findings in accident reconstructions. These "injury criteria" use acceleration, force, moment, or relative displacement data to predict some injury in the human. For example, injury criteria have been suggested for the latest approved automotive dummy (the Hybrid III) to define head injury; facial laceration; neck flexion extension, tension, compression and shear; chest compression from belt loads or distributed loads; axial and combined axial and bending femur loads; medial and lateral tibial loads; ankle compression and knee laceration.

While such measurements are important for understanding the overall performance of a seating system, no criteria exists for predicting injury from vertical impact loads, and the absence of biofidelity in the vertical direction for this dummy precludes obtaining accurate criteria. The lack of suitable anthropomorphic dummies for evaluating the performance of crashworthy seats in dynamic tests is a severe limitation on the validity of that procedure.

Notes for Chapter 3

Note 1: The reluctance of the public to accept crash safety as a product improvement was also seen in the automobile industry. In 1955, Ford Motor Company initiated an unprecedented campaign to inform the public of the new safety features in their automobiles. Safety door locks to help prevent ejection of passengers, rear view mirrors which would break free rather than cause injury, and an energy absorbing steering wheel designed to distribute the load on the chest and reduce injury were standard features. Seat belts and padded instrument panels were optional. When Ford automobile sales fell behind those of the General Motors Chevrolet, an industry saying that "Ford sold safety and Chevrolet sold cars" served to disinterest management in further safety promotions.

Note 2: Many of the people at AvSER, dismayed at the movement away from aviation safety research, managed to relocate and continue their efforts. Among others, Turnbow became Director of the Crash Injury Investigators School at Arizona State University and then Co-Director of the Crash Survival Investigation School of the International Center for Safety Education; Robertson formed his own companies, Robertson Research and Robertson Aviation, to develop improved crash safety technology (primarily related to crashworthy fuel systems) and became Director of the International Center for Safety Education; Haley joined the U.S. Army Agency for Aviation Safety and then the U.S. Army Aeromedical Research Laboratory as Chief of the crashworthiness section and was active in the U.S. Army's movement toward crashworthy helicopters; Desjardins formed Simula, Inc. which became a prominent developer and manufacturer of crashworthy seating systems; Carroll joined the National Transportation Safety Board; and Laananen continued to work on computer modeling of the seat/restraint/occupant to crash impacts while at the Pennsylvania State University, Simula, Inc., and Arizona State University.

Note 3: Several versions of the ceiling mounted troop and passenger seats have been evaluated in dynamic tests by the FAA Civil Aeromedical Laboratory in cooperation with the U.S. Army. Improvements made during the testing of the Boeing-Vertol prototype seats resulted in a system which had potential for good performance in the field. However, the other systems suffered structural failures in those tests which would limit their ability to protect occupants during an aircraft crash. In any event, this seat design concept has some characteristics which could adversely affect performance. The diagonal struts provided for longitudinal stability in forward facing seats will pivot about their attachment fitting on the floor during a crash with vertical impact forces. As this strut pivots, the front edge of the seat frame will follow a circular path having a center at the pivot point, and thus move forward and downward, towards the lower legs of the occupant. If the legs are in the path of the seat movement, the front edge of the seat could cause serious injury to the lower legs. This injury is not addressed in the seat requirements. A second problem is related to the crossed cables provided for lateral stability. If these cables are of such a length that they will be tight when installed, the proper installation becomes very difficult. This difficulty is compounded if there are wide tolerances in the location of the attachment points on the floor. Since the seats are intended to be rapidly removed or installed under adverse field conditions, any installation difficulties will probably result in non-use of the seats. Yet, if the cables are slack so that installation is easy, they may snap and fail under the rapidly applied crash loads, even though they may perform adequately under gradually applied static test loads. A third problem is that the performance of the seat cannot be predicted after the overhead energy absorbers have stroked. This action, in effect, introduces slack into the seat suspension. Any subsequent aircraft motion during the crash sequence will find the seat, and occupant free to move in any direction within the limits of that slack. The potential for injurious secondary impact between the seat occupant and the interior of the aircraft is obvious.

Note 4: The armored crashworthy crew seat which was developed in conjunction with Mil-S-58095(AV) (Desjardins and Harrison, 1972) provided a basis for the prototype seats for the UH-60A. Development tests of these prototypes were performed by the Naval Air Development Center at Warminster, Pennsylvania. These tests proved functional feasibility of the design concept and provided performance data. However, Sikorsky, the prime contractor for the UH-60, established stringent requirements for weight control. The contract finally negotiated among Sikorsky, Norton, and Simula for the production seat required that the weight of the prototype seats be reduced by about 22 pounds. This was achieved through a total redesign of the basic supporting structure for the seat, removing redundant structure and using fairly sophisticated fabrication techniques. This increased the cost of the seat, and the cost to the Government was compounded by the three-tiered contractor arrangement. After delivery of the first helicopters, the Army concluded that the seat weight was not that critical in the production aircraft, and relaxed the seat weight restriction. This allowed the heavier but less costly Joint Army-Navy ARA seat to be considered for use. The Army then decided to provide seats for future deliveries of UH-60 helicopters, and initiated a competitive procurement action for the seats. After a lengthy and somewhat complex procurement action, the JAN-ARA seat was selected for follow-on production of the aircraft.

Note 5: The study indicated that, in most crashes, only the vertical velocity change decreased to zero during the major impact. If the corresponding stopping distance is known, a simple calculation can yield the average acceleration in the crash. In other cases, the average acceleration was estimated by comparison of accident configurations and damage with data from controlled crash tests, from observations of failure or non-failure of seats or restraints of known strength, and by comparison of injuries with generally accepted human tolerance data. This is an important consideration when trying to establish dynamic test procedures for occupant protection systems. If these seats or restraint systems are designed for energy absorption, it would seem proper to evaluate them in laboratory test conditions which provide energy equivalent to that which exists in the crashes. The longitudinal impact in many crashes is characterized by an initial high G crash pulse, followed by a long, low G, slide out until the aircraft stops. The longitudinal velocity measured in crash tests is often reported only as the velocity change of the initial high G impact, or of some other high G segment of the overall crash deceleration. Such data reports are correct in the sense that nothing more than a velocity change is claimed for the data. However, the energy contained in a crash pulse is proportional to the difference between the square of the velocity at the beginning of the impact pulse and the velocity at the end of the impact pulse. Equating a velocity change measured in a crash to the velocity change required in a laboratory impact test with zero final velocity could result in a laboratory test condition which generates only a small portion of the energy in the segment of the crash.

Note 6. Inversion tube energy absorbers tend to be unstable when stressed under compression loads. This was known at the time of crash test T-41, but it was decided to use the seat as designed, without modifications to place the energy absorbers in tension.

Note 7: The Piper seat was one of the first seats for small airplanes which depended on intentional seat deformation for energy absorption and for allowing the seat to remain attached to a warped floor. As such, it became the model for several later seat developments. Unfortunately, although the seat was an energy absorbing seat, the shoulder belt was attached high on the airframe at one end, and to the seat belt on the other end. When the seat stroked downward to absorb energy in the vertical direction, the shoulder belt could prevent the seat belt from following the downward motion. While this action could theoretically allow the occupant to submarine under the seat belt, in practice it caused few problems, perhaps because few occupants bothered to use the shoulder belt. The NACA Ames seat concept provided an inner seat bucket which was suspended in a large outer shell by cables attached to energy absorbers. After the energy absorbers stroked, the inner seat bucket was no longer held firmly in place, but was free to move within the constraints of slack energy absorber cables and the clearances with the outer bucket. This made it difficult to control the reaction of the occupant in the event of a second impact. The concept was never developed beyond the trial stage.

Note 8: This analysis of fatalities and injuries in general aviation crashes in which fire occurred considerably altered previous estimates which were based on analysis which had no consideration of the effects of acceleration injuries.

Note 9: The General Aviation Safety Panel included representatives of Baker Flying Service, Business and Commercial Aviation magazine, Piper Aircraft Corporation, U.S. Aviation Underwriters, Inc., Flying Magazine, the Flight Safety Foundation, the Air Traffic Control Association, the Avionics Engineering Center of the Ohio University, the Aircraft Owners and Pilots Association, the National Business Aircraft Association, the Experimental Aircraft Association, the Aircraft Owners and Pilots Air Safety Foundation, and Flight Safety International, Inc.. Participating in the working group were representatives of the Aerospace Industries Association (Douglas and Lockheed Aircraft), Aeroquip Aerospace Corporation, the Aircraft Owners and Pilots Association, Beech Aircraft, Bell Helicopter Textron, Inc., Business and Commercial Aviation magazine, Cessna Aircraft, the Experimental Aircraft Association, FAA (Headquarters, Civil Aeromedical Institute, Office of Aviation Medicine, Small Airplane, Transport and Rotorcraft Directorates, Technical Center), Fairchild Aircraft Corp., the Flight Safety Foundation, the General Aviation Manufacturers Association, Gulfstream Aerospace, Mooney Aircraft, NASA (Headquarters and the Langley Research Center), the National Transportation Safety Board, Pacific Scientific, Piper Aircraft, Simula, Inc., RMS Technologies, Sikorsky Aircraft and the U.S. Army Aeromedical Research Laboratories.

Note 10: Premature release of the seat belt buckle had been previously observed on dynamic tests at CAMI (e.g., Singley, 1981). The traditional proof of restraint system performance had been based on static tests of the lap belt portion alone, supplemented by static tests of the shoulder belt portion, alone. However, the combined lap belt and shoulder belt(s) would sometimes release during a dynamic test. This was due to the misalignment of the latch plate(s) in the buckle of the belt, caused by the upward pull of the shoulder belt(s) on the lap belt. The misalignment could result in point-loading between the latch plate and the latching pawl in the buckle, and the resulting high stress would cause failure of those components. Alternately, the misalignment could result in a wedging action which could pull the latch plate over its pawl in the buckle, releasing the restraint. These problems led to the development of a static test procedure which would simultaneously load the lap belt and shoulder belt portions of the restraint system and create the potential for misalignment problems (Ross, 1975). This procedure was subsequently incorporated into the new standard for restraint system testing (Jaeger, 1985).

Note 11: Although the forces and moments transmitted to the attachment points were routinely measured in the CAMI tests, a requirement to make these measurements in tests conducted at other facilities would be costly, and was therefore not considered. However, these data are of considerable value to the designer, and several manufacturers who have conducted tests at facilities other than CAMI have requested that these data be obtained in those tests.

Note 12: A new, and more costly, anthropomorphic dummy was being developed by the automobile industry as the aircraft seat testing recommendations were being defined. This new dummy, now described in the U.S. Code of Federal Regulations, Title 49, Part 572, Subpart E, (the Hybrid III) has several improved features which are of importance in automobile applications, but are not critical for the aircraft seat and restraint system tests. It offers no significant improvement of performance in the vertical (spinal) impact conditions, where improved dummy performance would be helpful. Moreover, because of differences in mass distribution between the Hybrid II and Hybrid III dummies, each dummy generates a different lumbar column load when subjected to vertical impact. Because the criteria in the GASP recommendations was developed with the Hybrid II dummy, the use of the Hybrid III dummy in these tests is inappropriate.

Note 13: It should be noted that the designs of most energy absorbing seats manufactured for civil aircraft have used deformation of the seat structure for energy absorption, rather than special energy absorbing links in a pivoting or sliding mechanism, as is characteristic in the designs of most energy absorbing seats for military aircraft. Good [illegible] can be advanced for or against either approach. It would appear that the use of [illegible] in a vertical test of a seat with sliding or pivoting linkage would be [illegible] to demonstrate that the [illegible] linkage did not [illegible] the seat [illegible] energy absorption.

Note 14: The Society of Automotive Engineers is a professional organization established [illegible] technology. It is most active in areas related [illegible]. As part of this activity, the SAE develops voluntary standards [illegible] and frequently develops Aerospace Standards [illegible] referenced in FAA Technical Standard Orders (TSO). A [illegible] the only means of [illegible] Federal Regulations.

[illegible] representatives from Cessna, Beech and Bell [illegible] General Aviation Manufacturers Association, American [illegible] and the FAA. In addition, [illegible] requested to participate by being placed on [illegible] these members was considered [illegible] of the standard. Preliminary copies of the proposed standard were circulated by the SAE and the GAMA to an extended list of interested parties. All comments and suggestions received from these parties were used by the committee in developing the final Aerospace Standard.

Note 16: This technique observes that the elongation limit of a linear spring in a simple mass-spring system can be defined in a plot by two lines parallel to orthogonal axes of permissible change in applied velocity and permissible average acceleration. The line perpendicular to the axis representing change in velocity can be thought of as representing the minimum velocity change needed in an impulsive type of impact which would be required for the spring to exceed its limit. The line perpendicular to the axis of average acceleration can be thought of as the minimum sustained acceleration (static load) required to stretch the spring to its limit. The intersection of the parallel lines is dependent upon the natural frequency of the system The shapes of the lines near the intersection point are not linear, and depend on the shape of the transient impact pulse. Unfortunately, most dynamic tests of seats, restraints and occupants have velocity changes and average accelerations which cause the test to fall near the intersection of the two lines.

Note 17: Similar results were reported by Sarrailhe (1979).

Note 18: Redesign of the body block so that the "pull point" is lower would do much to improve the relationship between forward static and dynamic loading for seats equipped with only a lap belt. For example, the "Lower Torso Block" described in the SAE Aerospace Standard 8049, Performance Standard for Seats in Civil Rotorcraft and Transport Airplanes, has a pull point located 125 mm (5.0 inches) above the seat cushion. This body block was derived from a similar device used to test automobile seat belt anchorages.

Note 19: The seats used in this program were designed for installation in narrow body Boeing airplanes. The floor track used for attaching the seats to the floor in this airplane is arranged so that the two occupants in the center and overhang seats will load the inboard pair of seat legs, while the outboard pair of seat legs stabilize the seat but carry no significant load. When three occupants are in these seats, the loads are more evenly distributed between the inboard and outboard seat legs, so that the maximum load in the critical (inboard) pair of seat legs is reduced even though the overall sum of the loads in both pair of legs is increased by three occupants. This would not be the case for seats designed for installation in aircraft with more optimal arrangement of floor track. Of course, improved location of floor track could also decrease the floor loading from the seats, and thus could allow the floor to accommodate greater crash loads from the seats before it breaks.

Note 20: It is interesting that this 93 pound seat carried three 250 pound occupants, for a seat weight to occupant weight ratio of (93/750) 0.124. Applying that same ratio to a seat designed for three 50th percentile occupants (170 pounds each) would yield a seat weight of less than 64 pounds. This is not significantly different from many lightweight forward facing seats. It would appear that the argument that rear facing seats are heavier and cause high floor loads could be repudiated by the technology advanced in the Weber rear facing seat.

Note 21: This study was submitted by Simula, Inc., for the FAA's official docket in response to the 1980 FAA hearings on transport aircraft seat strength.

Note 22: It has been suggested that it would be wise to for a passengers to put their feet on the seat in front of them, and push hard against the seat with their legs when attempting to brace for a crash. Such an effort could significantly increase the loads on the seat in front, and may cause it to fail. This would be to the disadvantage of all the passengers involved, especially those in the seat in front. This procedure is not recommended.

Chapter 4. POSTCRASH SURVIVAL

Fire. This brief summary will touch upon some of the factors which improve the immediate postcrash survival of aircraft occupants. Minimum requirements for the performance of postcrash survival designs are given in the Federal Regulations or in Military Specifications. It is well to remember that these are minimum requirements, and should be exceeded whenever possible because of the unpredictable nature of postcrash survival.

Historically, accident studies have attributed a large number of fatalities in aircraft crashes to the consequences of a postcrash fire rather than the impact itself. While the true extent of debilitation caused by the crash to these fatalities will never be know, it is apparent that the prevention of postcrash fires is an important factor in preventing deaths in aircraft crashes. The technology for postcrash fire prevention in helicopters has been developed and put into practice. In 1968, the U.S. Army began development of a crashworthy fuel system (CWFS) for the UH-1 helicopter (Knapp, 1981). The first production helicopter equipped with a CWFS fuel system were delivered in 1970. Accident data soon showed that there were no thermal injuries in crashes of CWFS equipped aircraft. These data justified a retrofit program for CWFS installation in other Army helicopters. Since the introduction of CWFS, thermal injury as a cause of death has been reduced from 14 percent (in 1969) to almost zero (Hicks, 1982).

Attempts to promote CWFS for other aircraft has not yet been successful. The failure of the Boeing 720 airplane AMK fuel system to prevent a fire in the FAA-NASA CID crash test, previously discussed, decreased the emphasis for implementing that technology on large transport airplanes. The conclusion of the GASP II panel that crashworthy fuel tank bladders would not be practical in the wing tanks of small general aviation airplanes, also previously discussed, means that the source of fuel will continue to provide a potential for post crash fires. At present, it appears that fuselage fuel containment is more practical to attain than wing fuel containment.

The conditions of a crash greatly limit the techniques available for on-board suppression of major postcrash fires. The lack of power and frequent fuselage breakup prevents consideration of such concepts as forced smoke ventilation. Effective compartmentation of the cabin is difficult, offers only limited protection against internal fires, and could delay emergency evacuation of the aircraft. Aluminum aircraft skin can melt through in less than one minute when exposed to an intense fire. Fire protection of the cabin after the skin melts could be improved by a thermal barrier under the skin, but these techniques have not yet been fully developed. Similar protection of the cabin floor could delay the penetration of the floor by fire, and some form of fire resistant window shade could delay fire penetration through cabin windows.

Should a postcrash fire take place, the occupants of the aircraft will be exposed to high temperature and smoke. Since crash conditions vary widely, the buildup of fire and the toxic effects of gases in the smoke are difficult to predict. Moreover, human tolerance to short duration high temperatures, particularly with regard to respiratory system injury, are not defined. Likewise, there is no consensus as to the human tolerance to combustion gases. Some studies indicate that an individual's judgement becomes impaired when the saturation of carboxyhemoglobin in the blood reaches 35 percent. This could occur if the individual breathes 3 percent carbon monoxide for 90 seconds. Other gases, such as hydrogen cyanide, hydrogen chloride, nitrogen dioxide, are common in aircraft fires and will decrease human tolerance even further, especially when acting in combination. Particulate matter in the smoke can block vision, get into the eyes so that the individual is forced to close them, and enter the respiratory tract, causing severe coughing and choking. Personal protective devices for the passengers (smoke hoods) have been developed, but the concern that attempts to use the devices will delay egress from the burning aircraft has prevented their widespread use.

Polyurethane foam, often used for seat cushions, has been identified as a major contributor to fire, flashover, and the production of toxic gases. Fire blocking, i.e., the insertion of a layer of fire blocking material over the foam, has been shown to delay flashover as much as 60 seconds.
Research is presently underway to develop materials for interior structural and trim components which exhibit greater fire resistance and lower smoke and toxic gas emission than conventional materials. Inflatable evacuation slides will withstand the radiant heat of a postcrash fire for a longer time if they are provided with a reflective coating. On-board fire suppression systems are a viable means of extinguishing in-flight fires, but their effective performance in postcrash fires has not been demonstrated.

Once a postcrash fire has started, the occupant should exit the aircraft as rapidly as possible. The available escape time depends upon the crash conditions, but can be as low as 7 seconds in helicopters (Johnson, 1989). A CWFS can extend the evacuation time to about 30 seconds. Adequate emergency exits must be provided to enable rapid evacuation of the aircraft. Evacuation times are usually determined by actual tests, using people who represent the occupants most likely to use the aircraft. The conditions for emergency evacuation conditions try to simulate the conditions of a crash, insofar as possible. Evacuation demonstrations for large transport airplanes typically show that the maximum number of occupants (maximum seating capacity) can evacuate the airplane in 90 seconds, in emergency lighting conditions, using only half of the exits. The passenger mix is chosen to represent the passengers who normally use the airplane. These test subjects must not have "practiced" evacuating the airplane. Only half the exits are used because an actual crash may have damaged or blocked some exits. Exits along one side of the exit are often blocked for the demonstration in the assumption that a post crash fire might exist on that side. These test conditions do not represent the combination of "worst conditions" that could exist. For example, the cabin might be filled with smoke, effectively blocking vision, the aircraft might be pitched up or rolled to simulate a postcrash attitude, and "panic" or non-action might exist among some passengers. The combination of the "worst case" conditions could preclude the evacuation of the aircraft, as shown by some actual incidents. However, any accident demonstration represents just one combination of test conditions, while there are a variety of conditions which might occur. The costs of evacuation demonstrations preclude tests involving all combinations. Computer models have been developed to aid in evaluating these other conditions, but they have not yet been validated.

The minimum number, type and size of the exits are usually provided in the regulations or specifications governing the type of aircraft, or in the U. S. Army Crash Survival Design Guide (for military helicopters). Exits (other than floor level exits) should not be high above the floor, and should not have excess drop to the ground outside the aircraft. If the occupants are expected to carry equipment during the flight, the exits should be sized to allow passage of the occupant and the equipment carried. Side exits should be evenly distributed throughout the passenger compartment. During an evacuation, the aircraft occupants will cluster at an exit until they can leave the aircraft. The flow of passengers through an exit becomes the limiting condition on evacuation time under those conditions. The effects of passenger clusters at exits may be minimized by staggering the exits on opposite sides of the fuselage. If the aircraft is likely to roll on its side during a crash, exits should be placed in the top side of the aircraft so that they can be reached after the roll. Exits should also be placed to facilitate evacuation in the event of ditching. Overhead exits are often the only practical means of leaving an aircraft that is rapidly sinking. Opening of side exits may allow water to enter the aircraft at a high rate, and decrease the available evacuation time. The method of opening an emergency exit should be rapid, simple, obvious and natural. No secondary operation, such as removing catches, locks or bars, should be required to open the emergency exit. Unless the aircraft is pressurized, emergency exits should fall free, outside the aircraft, once released. Removing an exit inward takes time, causes confusion, and adds to the clutter that can impede the evacuation.

Emergency interior lighting illuminates the interior of the aircraft if normal lighting is not available. Emergency interior lighting for use in emergency egress should illuminate the exit pathway and aid the occupants in finding and actuating the exits. Smoke will move to the top of the ceiling of an aircraft, and quickly obscure overhead emergency lights. Therefore, lights provided for emergency evacuations should be located near the floor. Light effectiveness is rapidly reduced by smoke. Bright lights will remain visible for a longer time in smoke conditions. Exterior emergency lighting should also be provided for aircraft in noncombat operations.

Ditching. Unplanned water landings (ditchings) are not uncommon for small aircraft that are frequently flown over water. Ditching is a premeditated maneuver deliberately executed with the intention of abandoning the aircraft. Unlike the uncontrolled crash into water, ditching offers reasonable chance for survival. Most fatalities in small aircraft ditchings are due to drowning.

Small fixed wing aircraft will generally float long enough after ditching to permit occupant evacuation. Over 88 percent of the occupants of these airplanes survive the ditching, and at least half of the fatalities are due to drowning after safe egress (Snyder, 1975). Helicopters are usually unstable in ditchings because of their high center of gravity. Most fatalities in helicopter ditchings are due to drowning, with the overall survival rate increasing as the flotation time of the aircraft increases. Air bags, large sponsons and sealed hulls are used to increase flotation time, but the overall effectiveness of these techniques in preventing fatalities has not yet been verified. In-rushing water is a problem in escape from a sinking aircraft, and underwater escape is made difficult by problems of disorientation, inability to reach or release the escape hatch, darkness, and difficulty in releasing restraints. High intensity escape hatch illumination increases the likelihood of successful egress underwater. Explosively cut exits can be used to provide additional openings for evacuation. Each of these exits should be manually activated so that only the desired exits are opened, since premature opening of a submerged exit could result in more rapid sinking. After all exits are submerged, automatic actuation of all exits could be used.

5. CONCLUSIONS AND RECOMMENDATIONS.

In the past 20 years, the design and fabrication of functional seat and restraint systems to provide crash protection in aircraft crashes has progressed from being an "art" to being an expression of practical technology. Functional energy absorbing seats and restraint systems have been used on production military helicopters, and crash investigations have proven their value, even when the crash environment exceeded the design limitations of the system. Programs for retrofit of crashworthy seating and restraint systems in earlier military helicopters are well underway. The energy absorbing characteristics of crashworthy seating systems have been adapted to limit the forces induced by the seats into the floor in a crash of these older designs, so that the overall system performance has been greatly improved. Skills for this technology are available internationally (e.g., Onishi, 1986; Vettes, Mens, CEAT, Martin-Baker, various cites).

This technology is now being applied to civil aircraft. Recent regulations by the U.S. Federal Aviation Administration have mandated improved crashworthy seat and restraint systems for newly certified small airplanes, large transport airplanes and helicopters. The rapid availability and acceptance of improved crashworthy passenger seats for transport airplanes led to retrofit of these seats in many existing airplanes, even before regulatory action requiring retrofit could be completed. Because crashworthy seats for civil aircraft are a relatively new development, their performance in actual crashes has not yet been determined. Preliminary data on a few crashes indicate that the new systems are performing well, but statistical data have not yet been generated. It is hoped that these data will be carefully collected and analyzed, and if changes are necessary in the regulations, the changes will be promptly made.

While this technology is practical, it is not trivial. Experience gained through failures in design and testing plays an important part in the success of subsequent designs. Until a manufacturer gains that experience, the transition to crashworthy seating systems will be tedious. And, while the technology is practical, it is still open to improvement. Specifications of crashworthiness requirements for future aircraft which are based on accident studies of old aircraft can be justified only if the new aircraft crash in the same manner as the old. If the crash environment changes, either because of different aircraft performance characteristics or different operational mission requirements, the specifications for crashworthiness should reflect those changes. Improvement in the methods for predicting the crash environment of new aircraft designs is needed.

Improvements in the technology for dynamic testing and for analysis of the data are also needed. While the uncertainties associated with dynamic testing are presently overshadowed by the uncertainties of the crash itself, more refined, and reproducible (among facilities) crash test procedures are needed. An anthropomorphic dummy which has good biofidelity for vertical impacts, as well as good biofidelity in other directions, is one of the more pressing requirements. Concurrent with the improved dummy, improved criteria for defining injury from the data obtained with the dummy should be developed. Criteria for injury in impact tests which have a vertical impact component are urgently needed. Instrumentation to obtain the data for calculating the injury criteria may also require development. And, as with any test device, factors of low cost, reliability, ease of repair, and the ability to precisely replicate the data output from identical test environments need to be incorporated in the improved dummy.

Continued development and improvement of seat and restraint systems is anticipated. Improved performance with lower cost and lighter weight should be the goal of these developments. The restraint system, in particular, appears to be limiting the performance of current systems. Improvements in webbing retractors are past due. Multiple axis sensing inertia reels, low cost powered retractors which activate at the very beginning of the impact, and webbing locking devices which can be located close to the occupant (to reduce problems caused by webbing elongation) are within the current state-of-the-art. The inflatable body and head restraint holds most promise for immediate development. If this system can be incorporated into a conventional restraint, without undue bulk or discomfort to the wearer of the system, it should be acceptable to the users. If the inflated bags can then be configured to provide reliable support to the head in a crash with both frontal and lateral impact directions, considerable progress will have been made. The possible use of aircraft mounted rapidly inflatable air bags to prevent secondary occupant impact with the cockpit interior also warrants investigation.

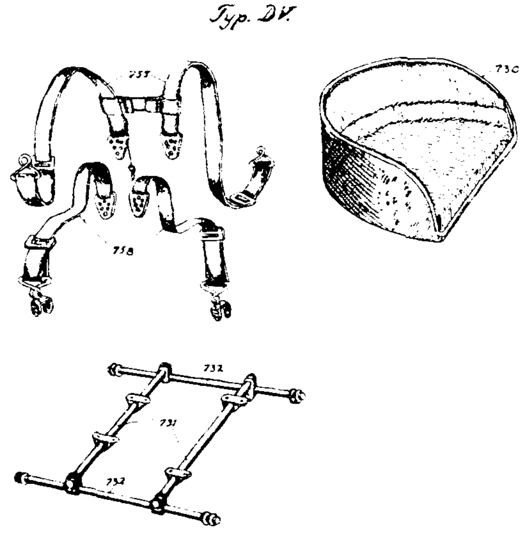


Figure 1. Albatros V Seat & Restraint

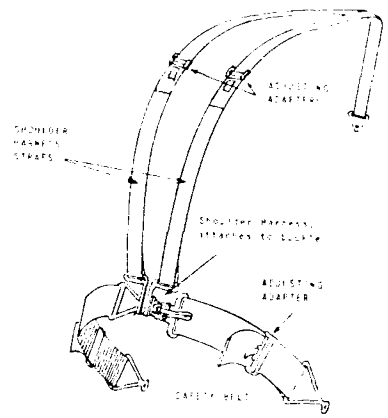


Figure 2. Early U.S. military aircraft pilot restraint system with shoulder harness (shoulder harness retractor not shown)

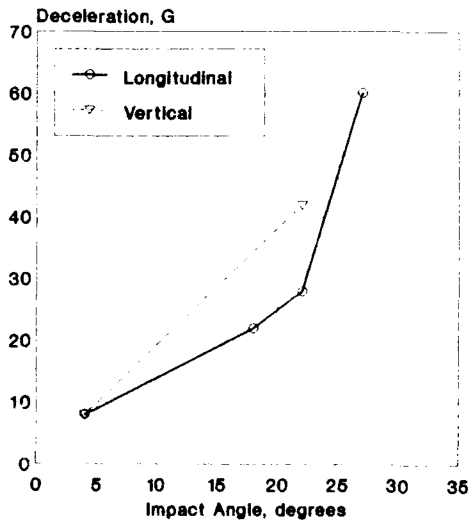


Figure 3. Deceleration of a low wing fighter airplane in 112 mph crashes (NACA tests)

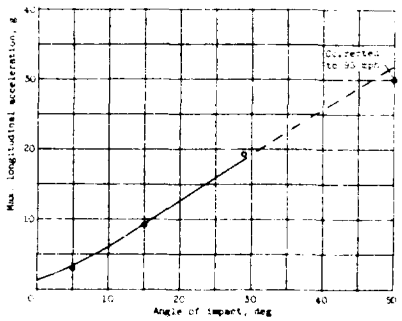
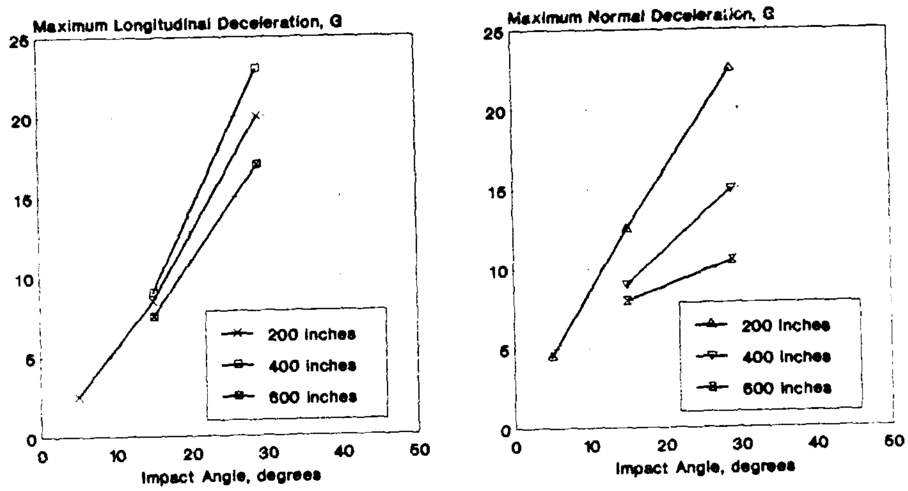


Figure 4. Longitudinal deceleration of pressurized transport airplanes in 95 mph crashes (NACA tests)



(a: longitudinal deceleration) (b: normal deceleration)
Figure 5. Deceleration measured along fuselage in crash tests (NACA tests)

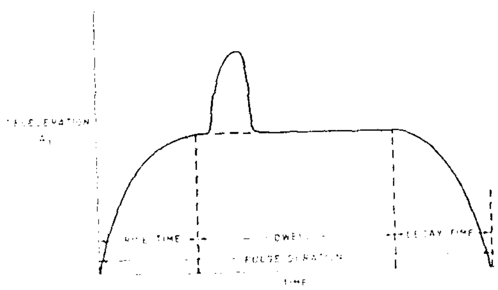


Figure 6. Deceleration pulse shape in NACA crash tests of airplanes

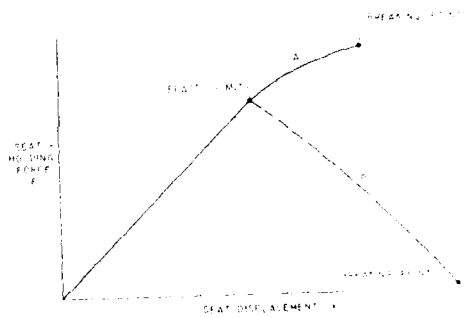
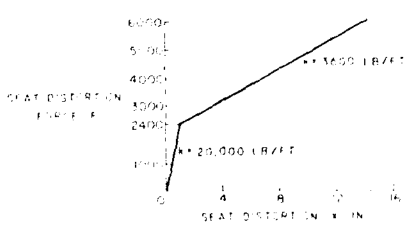


Figure 7. Unsatisfactory energy absorption characteristics beyond yield point (NACA)



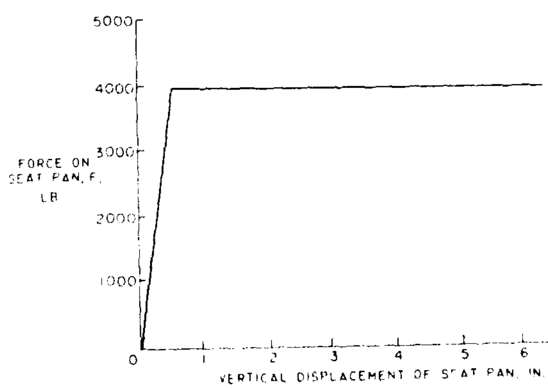


Figure 8. [illegible] seat distortion [illegible] natural frequency (NACA)

Figure 9. Force-displacement curve for vertical energy absorption (NACA)

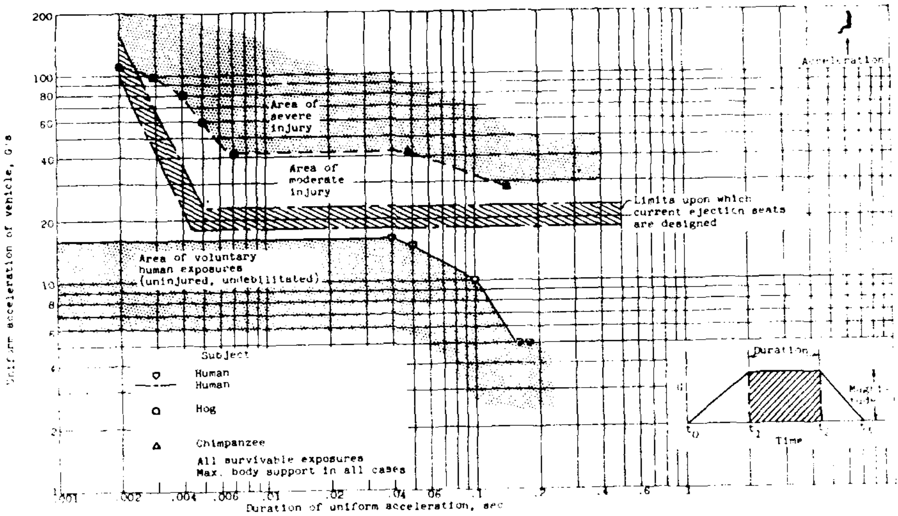
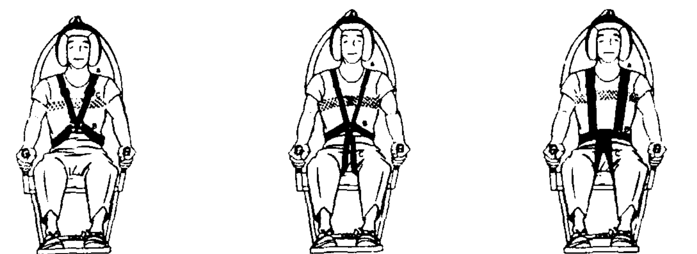


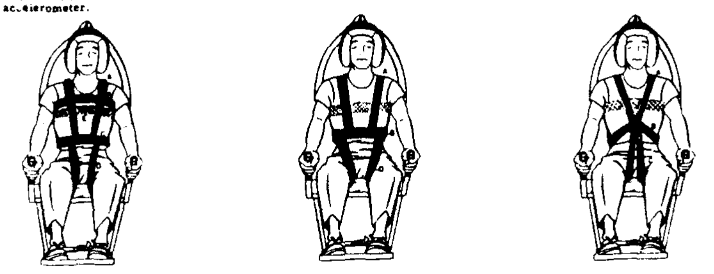
Figure 10. Fiband tolerance curve for headward acceleration (ACA)



Standard Air Force harness for forward facing seated subject. (a) Shoulder strap, No. 8 Nylon, 1-3/4 in. (b) No. 9 Nylon 3 in. Lap belt. (c) Slack safety chest strap with accelerometer.

Modified Air Force model with No. 10 Nylon, 1 3/4 in. shoulder strap. (a) Shoulder strap (b) Lap belt (c) Inverted-V leg strap.

Modified Air Force standard model with 3 in. No. 9 Nylon shoulder strap and inverted-V leg strap. (a) Shoulder strap. (b) Lap belt. (c) Inverted-V leg strap.



Maximum support research model harness, 3 in. No. 9 Nylon. (a) Shoulder strap (b) Chest belt (c) Lap belt. (d) Leg straps (e) Slack safety chest strap with accelerometer

Maximum support research model harness minus chest belt 3 inch No 9 Nylon throughout. (a) Shoulder strap. (b) Lap belt. (d) Leg strap

Research model minus chest strap with inverted V leg straps. (a) Shoulder strap. (b) Lap belt (c) Inverted-V leg strap.

Figure 11. Restraint development in forward facing human impact tests by Stapp.

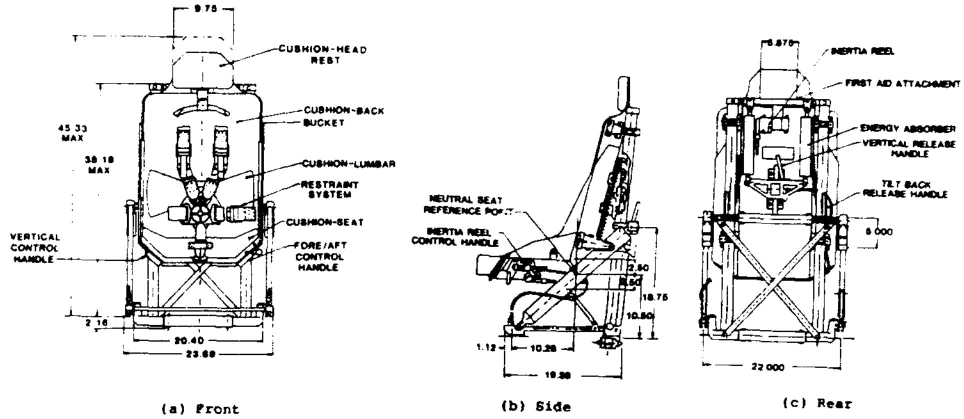


Figure 12. UH-60 Crew Seat

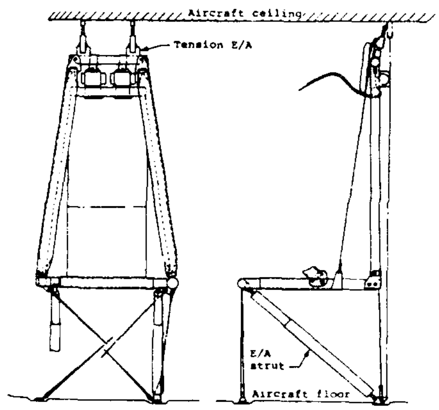


Figure 13. UH-60 Troop Seat

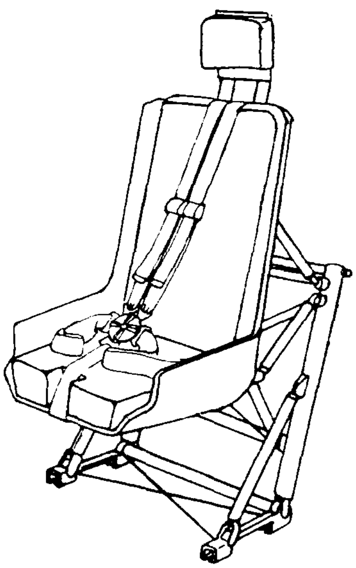


Figure 14. Joint Army-Navy Crew Seat

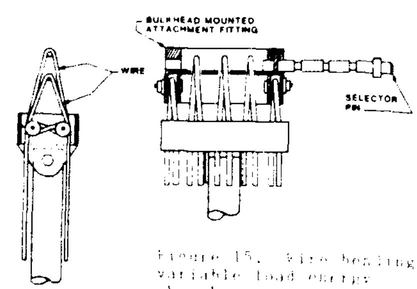


Figure 15. Wire bending variable load energy absorber

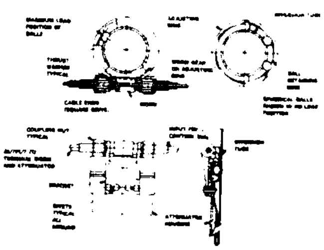


Figure 16. Tube/ball variable energy absorber

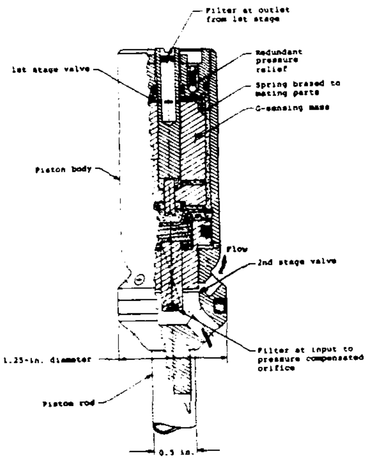


Figure 17. Automatic relief valve energy absorber

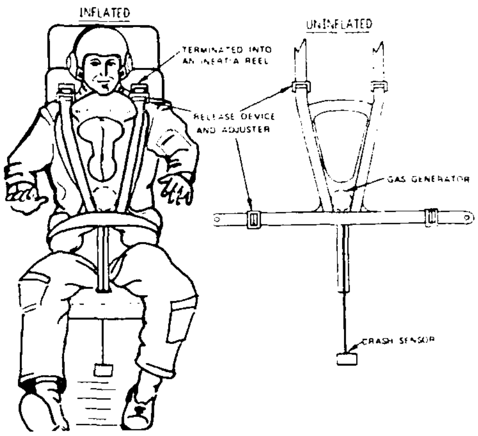


Figure 18. Prototype inflatable body and head restraint system

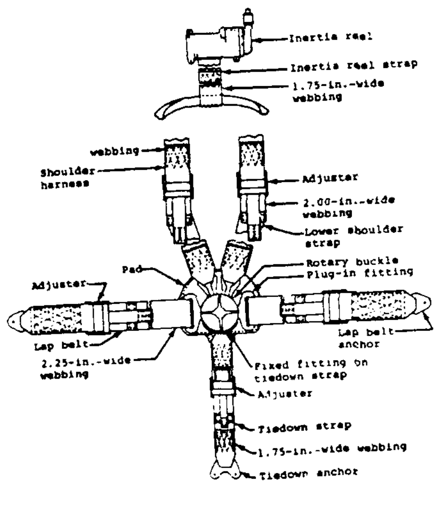


Figure 19. "MIL-S-58095" Restraint System

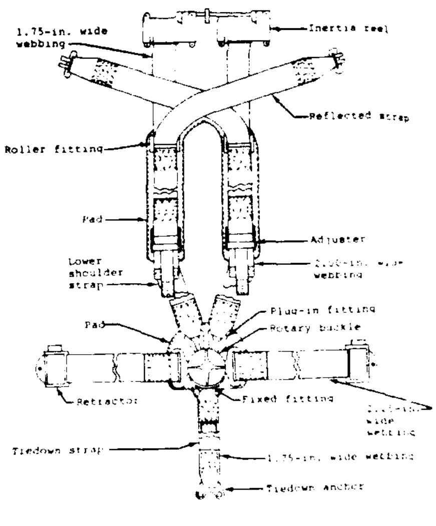


Figure 20. Reflected shoulder strap restraint system

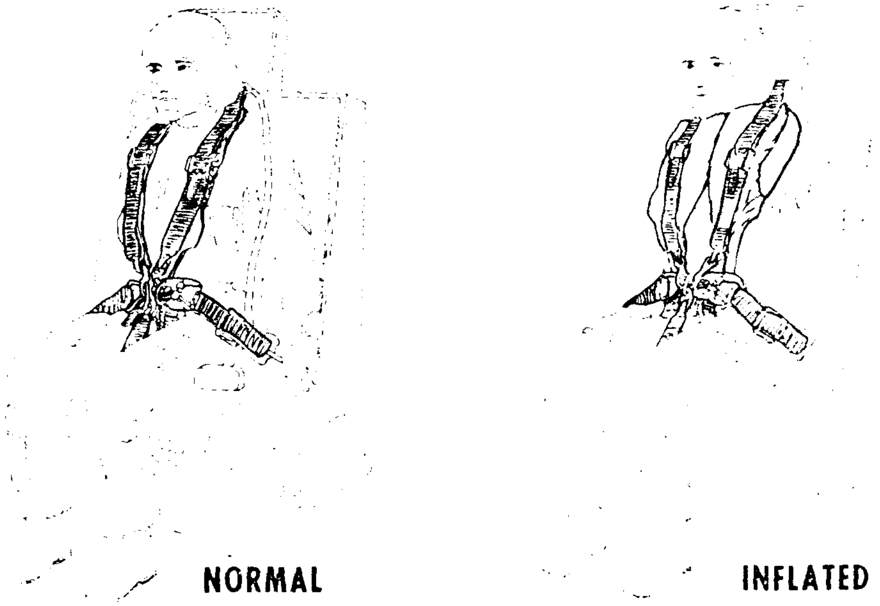


Figure 21. [illegible]

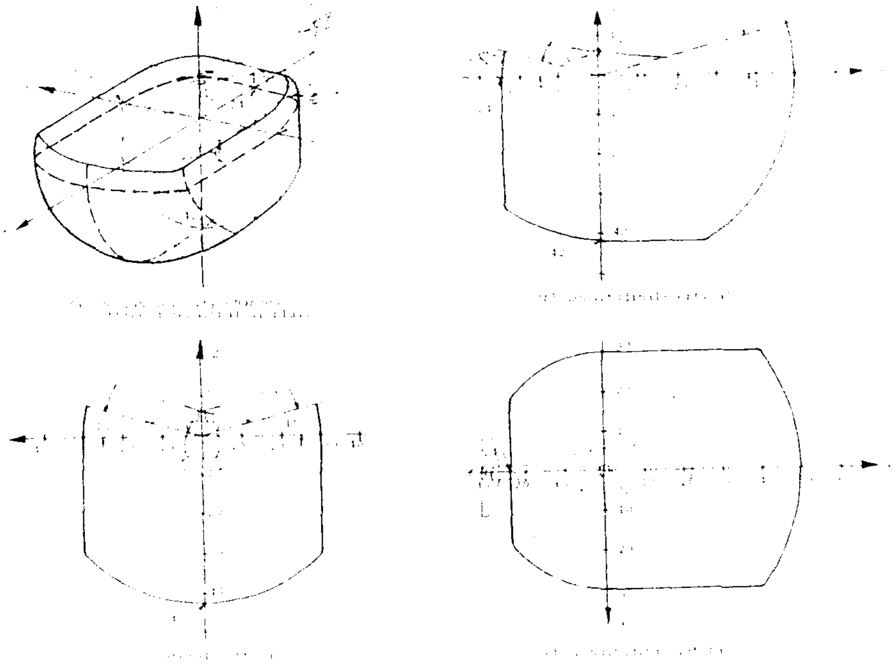


Figure [illegible]. Design Velocity Change for Military Helicopter [illegible]

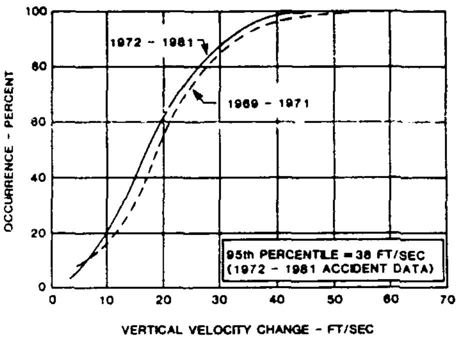


Figure 23. Vertical Velocity Change-Navy Helicopter Land Accidents

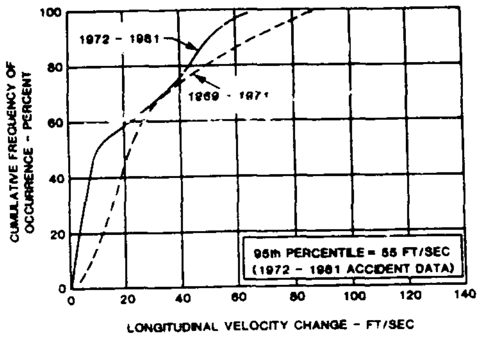


Figure 24. Longitudinal Velocity Change-Navy Helicopter Land Accidents

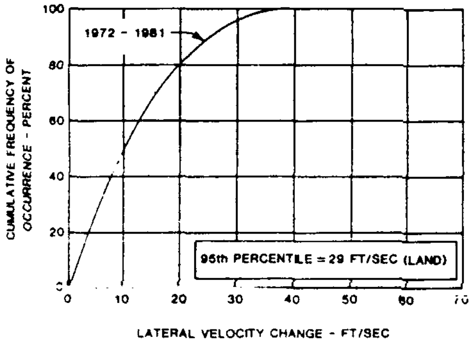


Figure 25. Lateral Velocity Change-Navy Helicopter Land Accidents

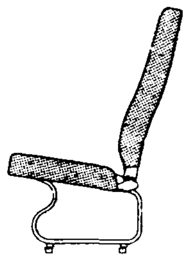


Figure 26. Piper Energy Absorbing Seat

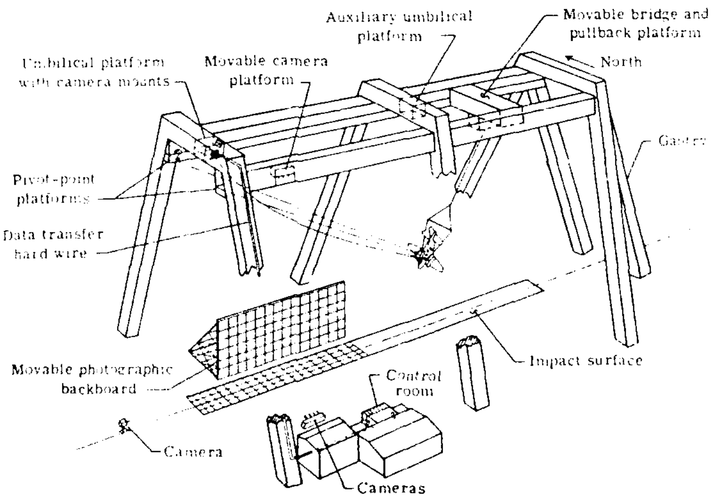


Figure 27. Langley Impact Dynamics Research Facility (NASA)

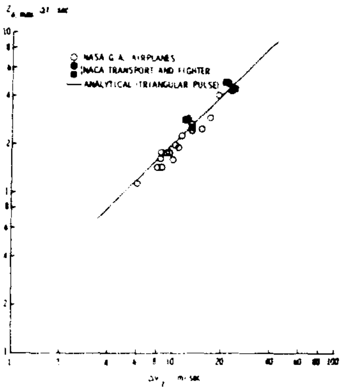


Figure 28. Experimental Impact Pulses in the Normal Direction (NASA)

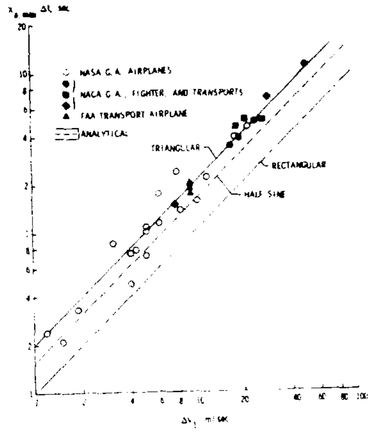
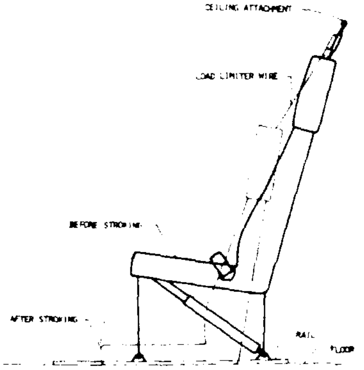
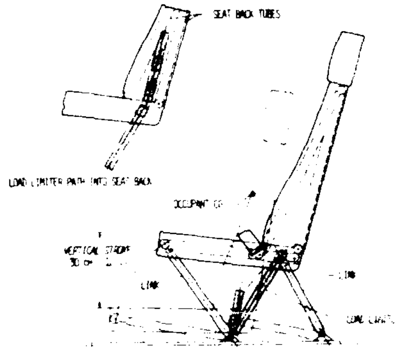


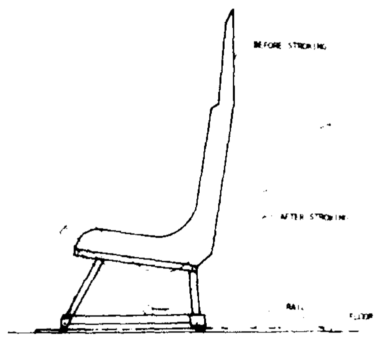
Figure 29. Experimental Impact Pulses in the Longitudinal Direction (NASA)



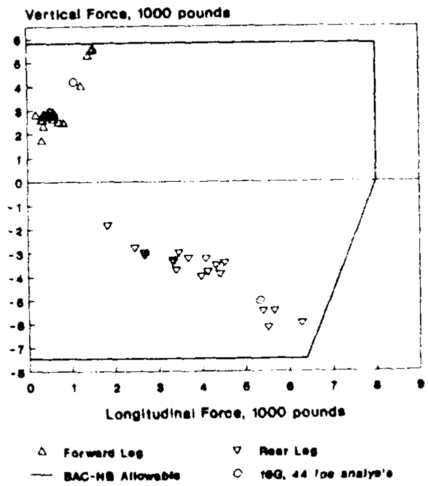
[illegible] Passenger Seat (NASA)



[illegible] Mounted [illegible] (NASA)



[illegible]



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Appendix A

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Appendix B

Transport Aircraft Crashes
(Minor Accidents and Incidents not Included)

ACCIDENT DATA

DATE	LOCATION	TYPE OF AIRCRAFT	PASSENGERS ON BOARD/ FATAL	REMARKS
01-08-75	Columbia	DC-3	/23	Crashed into mountain
01-15-75	Budapest	IL-18	/9	Crashed on landing in fog.
01-30-75	Santo Domingo	DC-3	/1	Crashed on takeoff, fire after impact.
01-30-75	Sea of Marmora	F-28	/41	Crashed into sea during approach.
02-16-75	Fairbanks, Alaska	DC-6	3 /2	Crashed during takeoff.
02-22-75	Columbia	CL-44	/5	Crashed into mountain.
03-12-75	Vietnam	DC-4	/26	Crashed en route (shot down by enemy fire?)
03-16-75	Argentina	F-28	52 /52	Crashed into Mt. Lopez and burst into flames.
03-20-75	Washington State	C-141	16 /16	Crashed into rain-swept Olympic Mountains.
03-31-75	Casper, Wyoming	B737	95 /0	Ran off runway, engine & gear torn away.
04-04-75	USAF, Vietnaim	C-5A	305/190	Crashed and burned shortly after takeoff.
04-24-75	Bolivia	CW-20	3 /3	Cargo plane crashed.
05-03-75	Columbia	DC-3	7 /7	Crashed on inaugeral flight.
05-10-75	Australia	Bristol 170	2 /1+1?	Crashed after an engine failure.
06-24-75	NYC/JFK	B-727	124/110	Severe downdraft, struck approach light, crashed inverted and burned.
07-02-75	France	B-99	8 /8	Crashed on takeoff (fire in engine after takeoff).
07-15-75	Batumi	Yak-40	/28	Crashed near Batumi on the Black Sea.
07-31-75	Taipei, Taiwan	Viscount	/28	Crashed during approach, rainstorm & low visabiliy
08-03-75	Agadir, Morocco	B-707	/188	Crashed into mountains on approach.
08-07-75	Denver, Colorado	B-727	131/0	Crashed in wheat field.
08-20-75	Damascus	IL-62	128/126	Crashed and burned during night landing.
08-30-75	Alaska	F-27	32 /10	Crashed on landing.
09-01-75	Leipzig	TU-134	34 /26	Touched down too soon and burst into flames.
09-24-75	Southern Sumatra	F-28	62 /26	Overshot runway, hit trees and burst into flames.
09-27-75	Miami, Florida	CL-44	11 /6	Crashed on takeoff.
09-30-75	Beirut	TU-154	64 /4	Crashed into Mediterranean Sea during approach. (exploded before plunging into sea?)
09-30-75	Columbia	B-727	4 /4	Missed the runway and crashed.
10-30-75	Prague	DC-9	/75	Crashed during landing approach in fog.
11-12-75	Raleigh, N. Carolina	B-727	139 /0	Impacted ground 85 M short of runway.
11-15-75	Near Buenos Aires	F-28	66 /0	Aircraft hit tree.
11-19-75	Guatemala	DC-3	/19	Crashed on landing.
11-22-75	Sofia, Bulgaria	AN-24	/2	Crashed on takeoff.
12-22-75	Milan, Italy	B-707	/0	Crashed on landing in fog.
01-02-76	Istanbul	DC-10	373 /0	Crashed on landing; skidded off runway.
01-03-76	Moscow	TU-134	87 /87	Crashed into houses after takeoff
01-15-76	Bogota	DC-4	/13	In bad weather enroute, hit mountain.
01-20-76	Equador	HS-748	41 /33	Crashed on 10000 foot peak, dense fog.
01-24-76	Shanghai, China	AN-24	/40	Crashed on its initial approach.
01-22-76	Chapeco, Brazil	EMB-110	9 /7	Crashed, burst a tire on takeoff.
02-04-76	Santa Marta, Col.	DC-6	/3	Crashed into sea after takeoff.
02-08-76	Van Nuys, Calif.	DC-6	/3	Engine failure after takeoff.
03-05-76	Yerevan, USSR	IL-18	/120	Crashed on approach.
03-07-76	Igiugig, Alaska	C-707	/4	Crashed enroute.
04-02-76	Colombia	DC-3	29 /5	Crashed after takeoff.
04-05-76	Ketchikan, Alaska	B-727	43 /1	Overran runway and burned.
04-14-76	Neuquen, Argentina	Turboprop	36 /35	Crashed in flames.
04-27-76	St. Thomas, VI	B727	88 /37	Crashed on landing.
05-09-76	Torrejon	B-747	17 /17	Crashed during a violent thunderstorm.
06-01-76	Malabo, Guinea	TU-154	46 /46	Crashed before landing, dense fog.
06-04-76	Guam	L-188A	45 /42+1g	Crashed and burned after taking off.
06-06-76	Borneo		11 /11	Spun into sea, two miles from airport.
06-23-76	Philadelphia	DC-9	104/0	Broke in half on landing during a thunderstorm.
07-28-76	Bratislava	IL-18	76 /71	Engine fire in flight.
08-02-76	Tehran	B-707	5 /5	Crashed shortly after taking off.
08-15-76	Quinto, Ecuador	Viscount	60 /60	Crashed during initial climb
09-04-76	Lajes, AFB Azores	C-130	68 /68	Crashed attempting to land in bad weather.
09-19-76	Isparta, Turkey	B-727	155/155	Crashed into mountain.
10-06-76	Bridgetown, Barbados	DC-8	78 /78	Crashed into sea after takeoff (inflight explosion)
10-12-76	Bombay, India	SE-210	99 /99	Crashed in flames, engine fire after takeoff.
10-14-76	Bolivia	B-707	/3	Crashed during takeoff.
10-25-76	Yopal, Columbia	DC-3	22 /22	Unsuccessful emergency landing, fire on impact.
11-04-76	Indonesia	F-27	38 /27	Crashed on landing.
11-16-76	Denver, Colorado	DC-9	/0	Aborted takeoff, fire after impact.
11-23-76	Kozani, Greece	YS-11	50 /50	Crashed into a mountain during stormy weather.
11-23-76	Zaire	L-382B	5 /4	Crashed at end of cargo run.
11-28-76	Moscow	TU-134	72 /72	Crashed shortly after takeoff.
12-16-76	Miami, Florida	880	3 /0	Aborted, overrun, stopped in canal.
12-24-76	Bangkok, Thailand	B-707	/51+20g	Crashed into factory during landing in fog.
01-13-77	Alma-Ata, U.S.S.R.	TU-104	92 /36	Engine fire/explosion during approach.
01-13-77	Anchorage, Alaska	DC-8	5 /5	Collision with ground; fire after immpact.
01-15-77	Stockhold, Sweden	Viscount	22 /22	Crashed during landing, lost control due to icing.
01-16-77	BWI	DC-8	95 /95	Aborted takeoff when an engine fire was detected.
02-09-77	Indonesia	HS-748		Crashed.
02-11-77	Bratislava	IL-14	5 /4	Crashed on approach.
02-28-77	Canada	DC-3	/4	Crashed during landing in low visibility.
03-01-77	South Yemen	DC-3	20 /19	Engine failure during climb/cruise.
03-03-77	Naimey, Nigeria	DC-8	4 /2	Cashed and burned while making an ILS approach.

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03-17-77	Prestwick	B-707	4 /0	Engine out training, large yaw and roll aircraft hit ground, slid out losing gear and engine.
03-27-77	Tenerife	B-747	394/332	Collision of two aircraft--
		B-747	248/248	one taxing, one on takeoff run.
04-02-77	Gabon	TU-134	8 /8	Crashed on landing.
04-04-77	New Hope, Georgia	DC-9	85 /70	Engine failure during cruise in hailstorm.
04-18-77	Tokyo, Japan	DC-8	140/0	Veered off runway, lost all gear and engines.
05-13-77	Beirut	AN-12	/9	Crashed in the hills near airport.
05-14-77	Lusaka, Zambia	B-707	/5	Crashed short of runway on approach.
05-16-77	New York, City	S-61 Helicopter	/5	Right gear collapsed, toppled on side at heliport.
05-27-77	Havana, Cuba	IL-62	68 /68	Crashed making an emergency landing in fog.
06-20-77	Salto, Uruguay	EMB-110	15 /5	Crashed on approach at airport.
07-07-77	St. Louis	L-188C	/3	Attempted takeoff. crashed left of end of runway.
07-17-77	Phillipines	YS-11A	25 /0	Crashed in sea off Mactan Island.
08-20-77	Costa Rica	CV-880	3 /3	Crashed on takeoff.
09-04-77	Cuenca, Ecuador	Viscount	33 /33	Crashed in the mountains on approach.
09-08-77	Keng Tung, Burma	Twin Otter	22 /22	Crashed in the mountains.
09-22-77	Bucharest, Hungary	TU-134	53 /29	Emergency landing, engine fire, crashed and burned.
09-29-77	Malasyia	DC-8	79 /34	Plunged into a 300-foot hill on landing descent.
10-18-77	Manila, Phillipines	HS-748	5 /2	Crashed near airport while on a local test flight.
11-19-77	Madeira	B-727	164/128	Overrun slid down 75 degree embankment hit bridge.
11-21-77	Bariloche, Arg.	FAC	79 /45	Impacted rocky area.
12-18-77	Madeira	CVL	57 /36	Aircraft touched down in water, passengers drowned.
12-18-77	Kayesville, Utah	DC-8	3 /3	Collided with mountain.
01-01-78	Bombay, India	B-747	/213	Crashed into sea shortly after takeoff.
01-18-78	Pueblo, Colorado	DHC-6	/6	Crashed during initial climb.
01-06-78	Zaire	F-27	/3	Crashed on takeoff in training flight.
01-28-78	Cerro Granada	DC-3	/12	Crashed into hill en route.
02-11-78	Cranbrook, B.C.	B-737	49 /42	Crashed on takeoff.
03-01-78	Los Angeles	DC-10	197/2	Blowout on takeoff, gear collapsed, caught fire
03-03-78	Santiago, Spain	DC-8	222/0	Aircraft broke in two, caught fire after landing.
03-03-78	Caracas, Venezuela	HS-748	/47	Crashed shortly after takeoff.
03-03-78	Santiago, Chile	DC-8	/0	Overshot runway.
03-16-78	Warsaw, Poland	TU-134	/73	Crashed en route.
03-24-78	Damascus, Syriua	TU-154	/4	Crashed on approach.
03-25-78	Rangoon, Burma	F-27	/48	Exploded and crashed after takeoff.
04-02-78	Sao Paulo, Brazil	B-737	42 /0	Wheels-up landing; fire after impact.
04-04-78	Charleroi, Belgium	B-737	3 /0	Crashed during landing on a training flight.
04-27-78	Apia, Western Samoa	CE-402	10 /10	Crashed when it hit a mountain.
04-29-78	Bogota, Columbia	DC-6	12 /8	Crashed shortly after takeoff.
05-09-78	Pensacola, Florida	B-727	52 /3	On night landing aircraft crashed into bay.
05-25-78	Miami, Florida	880	6 /0	Forward c.g. problem-A/C overrun and broke up.
06-03-78	Abu Dhabi	HB-212	15 /15	Crashed into sea.
06-08-78	Guatemala	DC-6	3 /3	Crashed and caught fire on landing.
06-25-78	Island of Bali	Helicopter	9 /9	Crashed in mountains.
06-26-78	West of Norway	S-61	18 /18	Plunged into the North Sea.
06-26-78	Toronto, Canada	DC-9	107/2	Aborted takeoff - slid down ravine, broke apart.
06-00-78	U.S.S.R.	TU-144	5 /2	Crashed on test flight.
08-03-78	Buenos Aires	B-707	64 /0	Crashed and burned on landing.
08-26-78	Burma	DHC-6	/14	Crashed on takeoff.
08-27-78	Cyprus	DC-6	/4	Crashed in hill en route.
09-02-78	Vancouver, BC	DHC-6	/11	Crashed into harbor and sank during approach.
09-03-78	Kariba, Rhodesia	Viscount	56 /48	Crashed after takeoff. Reported shot down.
09-03-78	Bamoko	IL-18	/15	Crashed in route in bad weather.
09-20-78	Monrovia, Liberia	DC-10	99 /0	Overray runway. Struck embankment.
10-04-78	Kuopio, Finland	DC-3	15 /15	Crashed into a lake.
10-26-78	Adak, Alaska	P-3C Orion	15 /3	Forced to ditch after prop failure & engine fires.
11-05-78	Egypt	DC-3	/17	Crashed shortly after takeoff.
11-15-78	Colombo, Sir Lanka	DC-8	259/195	Crashed during approach in bad weather.
11-20-78	Guadeloupe	DHC-6	/15	Crashed in thunderstorm on takeoff.
12-17-78	Hyderabad, India	B-727	126/1+3g	Crashed after takeoff, caught fire.
12-23-78	Palermo, Sicily	DC-9	129/108	Crashed into sea during approach.
12-28-78	Portland, Oregon	DC-8	189/10	Crashed during approach.
01-24-79	Morocco	Nord 262	/14	Crashed en route.
01-30-79	Near Tokyo	B707	/6	Cargo flight crashed en route to Los Angeles.
02-09-79	Miami, Florida	DC-9	5 /0	Loss of control on takeoff in training.
02-12-79	Rhodesia	Viscount	59 /59	Shot down by guerillas on approach.
02-13-79	Clarksburg, WV	Nord-98	24 /2	Crashed on takeoff in snow storm.
02-17-79	New Zealand	F-27	4 /2	Crashed during approach in heavy thunderstorms.
03-14-79	Peking, China	Trident	/12+200g	Crashed after takeoff.
03-14-79	Daha, Qatar	B-727	64 /45	Crashed on landing in heavy thunderstorm.
03-17-79	Moscow	TU-104	/90	Engine fire after takeoff.
03-29-79	Quebec	F-27	/11	Crashed en route.
04-18-79	Newark, New Jersey	S-61	18 /3	Crashed on takeoff.
04-23-79	Ecuador	Viscount	/52	Crashed en route.
04-26-79	Madras	737	67 /0	Overrun.
05-25-79	Chicago, Illinois	DC-10	/275	Crashed on takeoff.
05-31-79	Maine	Twin Otter	18 /17	Crashed attempting to land.
06-11-79	Idaho	DC-3	12 /10	Crashed into a river in rugged mountains in Idaho.
06-17-79	Hyannis Port	DHC-6	/1	Crashed during approach to landing.
07-11-79	Sumatra	F-28	61 /61	Crashed on a mountain peak.

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07-16-79		AC-114	/2	Crashed en route.
07-24-79	St. Croix	DH-114	21 /8	Crashed on takeoff.
07-26-79	Brazil	B-707	3 /3	Crashed shortly after takeoff.
07-31-79	Scotland	HS-748	47 /17	Crashed on takeoff.
10-07-79	Athens, Greece	DC-8	154/14	Overrun.
10-31-79	Mexico City, Mexico	DC-1	87 /70	Touchdown, hit vehicle.
01-21-80	Tehran, Iran	B-727	/129	Crashed into mountain in fog after takeoff.
01-23-80	Indonesia	C-212	13 /13	Crashed in bad weather.
02-27-80	Manila	B-707	/2	Crashed and burned on landing.
03-14-80	Warsaw, Poland	IL-72	87 /87	Crashed on approach.
03-14-80	Adana, Turkey	C-130H	18 /18	Crashed.
03-20-80	Macae City, Argen.	S-76	13 /13	Crashed into the sea.
03-23-80	Leeds/Bradford	CE-414	/2	Crashed during a safety check flight.
03-27-80	Denver, Colorado	BE-200	10 /10	Crashed shortly after takeoff.
04-13-80	Brazil	B-727	58 /54	Crashed in rainstorm.
04-25-80	Tenerife	B-727	/145	Crashed into mountain on approach.
04-27-80	Bankok	BAe-748	57 /40	Exploded on approach during thunderstorms.
05-18-80	Molokai, Hawaii	CH-53	9 /7	Helicopter crashed and burned.
06-02-80	Bolivia	F-27	13 /13	Crashed into mountain on approach.
06-07-80	Moscow	IL-18	/118	Crashed and exploded.
06-12-80	Valley, Nebraska	SA-226	15 /13	Crashed enroute.
06-27-80	Palermo, Italy	DC-9	/81	Crashed into sea enroute.
07-07-80	U.S.S.R.	Tu-154	/163	Crashed into ocean after takeoff.
08-01-80	Peru	DC-8	/7	Crashed into hill and exploded enroute.
08-08-80	Mauritania	TU-154	/160	Crashed into sea during approach.
08-26-80	Jakarta, Indonesia	Viscount	/31	Crashed on approach.
09-11-80	Brazil	DC-8	/4	Crashed in Amazon jungle enroute.
09-14-80	Medina,	C-130	89 /89	Crashed in flames at airport.
09-24-80	Iceland	BN-2A	/3	Crashed into the summit of Mount Smjorfjoll
11-03-80	Caracas	CV-880	/4	During takeoff lost an engine and crashed.
11-05-80	Benguela, Angola	B-737	/0	Crashed and burned on landing.
11-18-80	Korea	B-747	226/13	Crashed and burned on landing.
12-20-80	El Dorado, Ven.	B-707	/0	Crashed and burned on landing.
12-21-80	Columbia	SE-210	/68	Crashed enroute.
01-08-81	Guatemala City	L-188A	/6	Crashed into house and exploded after takeoff.
02-06-81	Karluk Lake, Alaska	CE-206	/1	Aircraft disappeared. Pax found floating in lake.
02-07-81	Leningrad	TU-134	/11	No details.
03-11-81	Ghana	F-28	/0	Crashed on training flight.
03-26-81	Poland	AN-24	/1	Crashed on landing approach, propeller failed.
04-28-81	Indonesia	DC-3	/9	Crashed on approach.
05-07-81	Buenos Aires	BAC 1-11	/30	Crashed enroute during heavy rainstorm.
05-20-81	Mexico	CV440	/21	Collided with high ground.
06-26-81	United Kingdom	HS 748	/3	Lost control on approach due to structure failure.
07-20-81	Mogadiscio	F-27	/49	Crashed and burned.
07-27-81	Mexico	DC-9	/50	Crashed on landing in thunderstorm.
08-22-81	Taiwan	B-737	/110	Crashed during climbout.
10-07-81	Netherlands	F-28	/17	Crashed enroute in severe turbulence.
10-31-81	Cameroun	Twin Otter	/1	Crashed on takeoff.
11-09-81	Mexico	DC-9	/18	Crashed into mountain during takeoff climb.
12-01-81	Corsica	DC-9	/174	Crashed into mountainside.
12-18-81	Columbia	Twin Otter	/14	Hit mountain.
01-13-82	Washington, D.C.	B-737	79 /74+4g	Hit bridge, crashed in river after takeoff (ice).
01-23-82	Boston	DC-10	212/2	Overran into the bay after landing.
01-25-82	Constantza, Romania	AN-24	/7	Veered off runway and hit buildings.
02-09-82	Tokyo	DC-8	174/24	Crashed into sea on landing approach.
02-25-82	Genting Highlands	Bell 212	11 /11	Crashed during thunderstorms after takeoff.
03-11-82	Norway	DHC-6-300	15 /15	Crashed into North Sea.
03-20-82	Sumatra	F-28	28 /27	Crashed on landing in heavy rain and burned.
03-26-82	Columbia	Viscount	22 /22	Crashed into mountain enroute to Bogota.
04-26-82	Guilin, China	Trident	112/112	Crashed into mountain on approach.
04-30-82	Thailand	S-76	13 /13	Helicopter crashed into sea.
05-09-82	Aden	DHC-7	49 /21	Crashed into sea on approach.
05-25-82	Brasilia	B-737	/2	Hard landing, aircraft broke in two.
05-28-82	Indonesia	SA-330G	10 /10	Ditched into sea.
06-02-82	Damascus	SE 210	84 /0	Belly landed.
06-08-82	Fortaleza, Brazil	B-727	137/137	Crashed into hillside on approach.
06-12-82	Tabatinga, Brazil	FH-227	44 /44	Crashed into airport parking lot.
06-22-82	Bombay	B-707	110/19	Overshot on landing in heavy rain.
07-06-82	Moscow	IL-62	/90	Crashed shortly after takeoff.
07-09-82	Kenner, Louisiana	B-727	145/145+8g	Crashed into residential area after takeoff.
07-28-82	Vans, Texas	CE-414	12 /12	Crashed on takeoff from private strip.
08-12-82	Mindat, Burma	DHC-6	8 /8	Crashed enroute in a rain storm.
09-11-82	West Germany	CH-47C	44 /44	U. S. Army helicopter crashed.
09-14-82	Malaga, Spain	DC-10	393/56	Skidded overran runway and caught fire on takeoff.
09-29-82	Luxemburg	IL-62	/7	Veered off runway after landing, caught fire.
10-17-82	Geneva	B-707	/0	Undershot the runway and caught fire.
12-09-82	La Serena, Chile	F-27	/44	Hit hill short of runway during approach.
12-24-82	Canton, China	IL-18	69 /23	Forced landing due to inflight fire.
01-03-83	Halley, Idaho	CL-600	2 /2	Crashed on approach on training flight.
01-09-83	Brainerd, Minnesota	CV-640	36 /1	Struck snowbank.
01-11-83	Detroit, Michigan	DC-8	3 /3	Crashed into swamp seconds after takeoff.
01-11-83	Toronto, Canada	Sabreliner	5 /5	Crashed on final approach.

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01-16-83	Ankara, Turkey	-727	67 /47	Crashed on landing in snowstorm, burned.
02-14-83	Strait of Malacca	GL-35A	6 /6	Crashed into the sea.
02-22-83	Manaus, Brazil	B-737	4 /4	Cargo plane crashed and burned on takeoff.
03-10-83	Afghanistan	YAK-40	19 /19	Crashed during storm.
03-11-83	Venezuela	DC-9	50 /20	Crashed on landing.
03-15-83	Sabha, Libya	B-707	5 /5	Crashed shortly after takeoff and burned.
04-16-83	Khartoum	HS-748	/8	Crashed into houses, burned after takeoff.
04-29-83	Guayaquil, Equador	SE-210	100/8	Crashed during emergency landing.
06-02-83	Indonesia	F-28	61 /3	Engine stalled and aircraft ran off end of runway.
06-02-83	Cincinnati, Ohio	DC-9	/23	In flight fire, crashed during emergency landing.
07-01-83	Labe, Guinea	IL-62	/23	Crashed into mountains.
07-04-83	Aberdeen, Scotland	SA-332	18 /0	Crashed on landing after a flight from an oil rig.
07-11-83	Cuenca, Ecuador	B-737	119/119	Crashed into a mountain during approach.
07-16-83	Isles of Scilly	S-61N	26 /20	Crashed into sea.
08-17-83	Grand Canyon	PA-31	10 /10	Crashed into a mountainside.
08-28-83	Avavale, Australia	BE-200	12 /12	Crashed.
08-30-83	Alma-Ata, U.S.S.R	TU-134		Crashed.
09-14-83	Guilin, China	Trident 2E	100/10	Collided with aircraft while taxiing.
09-23-83	Abu Dhabi	B-737	112/112	Crashed on scheduled flight.
10-11-83	Illinois	HS-748	10 /10	Crashed into rolling terrain, electrical failure.
11-08-83	Angola	B737	126/126	Crashed shortly after takeoff.
11-27-83	Madrid, Spain	B-747	/183	Crashed and exploded in hills east of airport.
11-28-83	Enugu, Nigeria	F-28	74 /53	Crashed and burned two miles from airport in fog.
12-07-83	Spain	B-727	93 /51	Collided in fog at airport. Takeoff.
		DC-9	42 /36	Landing.
01-10-84	Sofia, Bulgaria	TU-134A	50 /50	Crashed in snow and fog.
01-13-84	Papua, New Guinea	BN-2A	10 /10	Crashed in highlands.
02-09-84	Angola	B-737	/0	Crashed following an explosion on takeoff.
03-16-84	Bolivia	F-27M	23 /23	Crashed into mountain in inclement weather.
06-12-84	Jakarta, Indonesia	DC 9	/0	Broke in two on landing while on ferry flight.
06-28-84	Brazil	EMB 110	16 /18	Crashed into hillside in inclement weather.
08-02-84	Puerto Rico	BN 2A	9 /9	Crashed into ocean after takeoff.
08-04-84	Phillippines	BAC-1-11	/0	Overshot runway and fell into sea.
08-05-84	Dhaka, Bangladesh	F-27	50 /50	Crashed in bad weather during landing approach.
09-18-84	Quito, Equador	DC-8	44 /44+40g	Lost power after takeoff, crashed residential area.
10-15-84	Omsk, U.S.S.R.	TU-154	/150	Hit fuel truck on landing.
01-01-85	La Paz, Bolivia	B-727	29 /29	Crashed into the side of the Andes Mountains.
01-09-85	Kansas City	L-188	/3	Struck cooling tower of waste disposal plant. circiling airport.
01-18-85	Jinan, China	AN-24	38	Crashed during landing approach at airport.
01-19-85	Havana, Cuba	Il-80	/40	Crashed on climbout.
01-21-85	Reno, Nevada	L-188	71 /70	Crashed on climbout.
01-23-85	Medellin, Columbia	DHC-6	/23	Struck mountain.
01-23-85	Buga, Columbia	EMB-110P	/17	Crashed into high ground.
02-01-85	Minsk, U.S.S.R.	Tu-134	/80	Crashed on climbout.
02-06-85	Philadelphia, Penn.	DC-9	/0	Crashed on climbout.
02-07-85	Calcutta, India	B-737	/0	Hard landing.
02-19-85	Bilbao, Spain	B-727	/148	Struck television tower, hit mountainside, burned.
02-22-85	Timbuktu, Mali	An-24	51 /50	Crashed shortly after takeoff. Engine failure.
03-28-85	Florencia, Columbia	F-28	/46	Struck a mountain, under IFR conditions.
04-15-85	Phuket, Thailand	B-737	/11	Struck high ground.
05-28-85	Venezuela	CV-580	/13	Crashed on climbout.
05-31-85	Nashville, Tennessee	G-159	2 /2	Crashed when engine failed during climbout.
06-23-85	Diamantino, Brazil	EMB-110P	/17	Crashed on emergency landing attempt.
08-02-85	Dallas, Texas	L-1011	163/135	Apparent wind shear.
08-12-85	Tokyo, Japan	B-747	524/520	Apparent structural failure.
08-15-85	Aden, South Yemen	B-707	15 /2	Control loss on climbout, emergency landing.
08-22-85	Manchester, England	B-737	137/54	Engine failure on takeoff.
09-06-85	Milwaukee, Wisconsin	DC-9	31 /31	Engine failure on takeoff.
10-12-85	Putoa, Burma	F-27	/2	Landing.
12-12-85	Gander, Newfoundland	DC-8	/256	Possible icing on takeoff.
01-18-86	Guatemala	SE-210	/95	Crashed while circling airport.
01-27-86	Buenos Aires	B-707	/0	Overran runway and crashed in bad weather.
01-28-86	San Paulo, Brazil	B-737	/1	Overran taxiway and struck enbankment.
01-29-86	Los Mochis, Mexico	DC-3	/21	Struck hillside and burned during approach in fog.
02-05-86	Zaire	L-188	/2	Crashed while attempting an emergency landing.
02-16-86	Pescadores Islands	B-737	/13	Crashed into sea during aborted landing attempt.
02-21-86	Erie, Pennsylvania	DC-9	/0	Overran icy runway and struck high ground.
03-30-86	Pemba, Mozambique	An-26	/44	Engine failure shortly after takeoff.
03-31-86	Maravatio, Mexico	B-727	/166	Tire initiated inflight fire, crashed on mountain.
04-28-86	Near Tame, Colombia	DHC-6	/13	Crashed into high ground in bad weather.
06-10-86	Cairo, Egypt	F-27	/23	Emergency landing in adverse weather.
08-04-86	St. Vincent	DHC-6	/13	Crashed into sea during heavy rain squall.
09-30-86	Jakarta, Indonesia	DHC-6	/13	Crashed into mountain in bad weather.
10-04-86	Kelly AFB, Texas	L-382	3 /3	Crashed shortly after takeoff.
10-23-86	Lahore, Pakistan	F-27	/13	Undershot runway in low visibility.
12-12-86	East Berlin	Tu-134	81 /69	Crashed during landing in fog.
12-25-86	Saudi, Arabia	B-737	/67	Crashed short of runway (pilot wounded in hijack).
01-03-87	Abidjan	B-707	51 /49	Crashed into forest and burned after takeoff.
03-04-87		CASA-212-CC	22 /9	Crashed just inside runway threshold.
04-04-87	Medan, Sumatra	DC-9	45 /34	Lightning strike in inclement weather approach. Struck powerlines near runway threshold, crashed.

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04-08-87		L-382G	5 /5	Crashed in steep left turn during go-around.
04-13-87	Kansas City, Mo.	B-707-351C	4 /4	Aircraft crashed.
05-09-87	Warsaw, Poland	IL-62	/183	Crashed following explosion and fire.
06-21-87		F-27	45 /45	Crashed on a mountain side.
06-26-87	Baguio	HS748	50 /50	Crashed into a mountain.
08-16-87	Romulus, Michigan	DC-9	155/156	Crashed onto freeway shortly after takeoff.
11-15-87	Denver, Colorado	DC-9	62 /28	Crashed while taking off during snow storm.
12-07-87	San Luis Obispo	LA 144 43	/36	Suspected suicide/sabotage.

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